

SURFACE FINISH MEASUREMENT
FOR ADAPTIVE NUMERICAL CONTROL OF MACHINE TOOLS

Dipak Basu

A MAJOR TECHNICAL REPORT

in the

Faculty of Engineering

Presented in partial fulfilment of the requirements for

the Degree of Master of Engineering at

Sir George Williams University

Montreal, Canada

September 1974

TABLE OF CONTENTS

LIST OF FIGURES.....	v
ABSTRACT.....	vii
ACKNOWLEDGEMENT.....	viii
Chapter 1. INTRODUCTION	1
Chapter 2. DEVELOPMENT OF ADAPTIVE NUMERICAL CONTROL.....	6
Chapter 3. NUMERICALLY CONTROLLED MACHINE TOOL	
A PHYSICAL DESCRIPTION	
3.1 General Comments	14
3.2 Machining Systems	15
3.3 Components of a machining system	18
3.3.1 General Information Flow	18
3.3.2 Input Data	18
3.3.3 The Machine Tool	20
3.3.4 Sensing Devices	22
3.3.5 Control	24
3.4 Machine Tool types	25
Chapter 4. MACHINING PROCESS VARIABLES	28
Chapter 5. ADAPTIVE CONTROL TECHNIQUES	
5.1 Theory	41
5.2 The Control System	42
5.3 Hardware and Sensors	46

Chapter 6. SURFACE FINISH MEASUREMENT

6.1 Introduction	48
6.2 Surface Metrology	51
M-System	55
Maximum Peak-to-Valley Height	57
Average Roughness	57
Form Factors	59
Bearing Area Curve	61
Other Measures	61
E-System	63
Comparison of 'M' and 'E' Systems	67

Chapter 7. STATISTICAL ANALYSIS OF SURFACE FINISH

7.1 Introduction	70
7.2 Amplitude Distribution	70
7.3 Auto-correlation of a Profile	72
7.4 Power Spectral Density and Average Wavelength	73
7.5 Application of Average Wavelength parameter	76
7.6 General Remarks	76

Chapter 8. SURFACE FINISH MEASURING INSTRUMENTS

8.1 Introduction	78
8.2 Stylus-type Instruments	79
8.3 Electro-optical Instruments	83
8.4 Laser Interferometers	88
8.5 Surface Finish Control	91

Chapter 9. CONCLUSION

REFERENCES	100
------------------	-----

LIST OF FIGURES

Figure 1	Cost-Efficiency Relationship with or without Adaptive Control	11
Figure 2	Movements of a Drilling Machine	16
Figure 3	General Information Flow	19
Figure 4	Machining System - Block Diagram	21
Figure 5	Control System	26
Figure 6	Rate of Tool Wear vs. Temperature	34
Figure 7	Build-up of Chatter	37
Figure 8	Effect of Machine Deflection on Chip Thickness	37
Figure 9	Self-excited Chatter build-up	39
Figure 10	Adaptive Control System - Block Diagram	43
Figure 11	Adaptive Control System - Hardware Configuration	47
Figure 12	Typical relationships of Surface Roughness to Production time	49
Figure 13	Surface Texture representing the combined effects of three causes	52
Figure 14	Surface Profile showing Mean lines for the whole length and consecutive sample lengths	56
Figure 15	Mean-line Determination	56
Figure 16	Maximum Peak-to-Valley Height R_t	58
Figure 17	Centre Line Average Determination.....	58
Figure 18	Two surface contours with the same average deviation	58

Figure 19	Form Factor	60
Figure 20	Bearing Area Curve	60
Figure 21	Ten-point Height	62
Figure 22	Peak and Valley Intercepts	62
Figure 23	Envelope System	65
Figure 24	Envelope Profiles with different directions of Rolling Circle approach	65
Figure 25	Profile of a turned surface with envelopes of different rolling circle radii	66
Figure 26	M-System and E-System Mean lines for a ground surface profile	69
Figure 27	Amplitude Distribution	71
Figure 28	Auto-Correlation Function	71
Figure 29	Auto-correlation Functions for a ground surface profile, its M-System mean line and the envelope ..	74
Figure 30	Power Spectrum and Average Wavelength	77
Figure 31	Comparison of Fundamental to Average Wavelength ..	77
Figure 32	Stylus Geometry	82
Figure 33	Surface tracing produced by Oscillating Stylus mechanism	82
Figure 34	Passive Peak Detector and Filter Assembly Circuit	84
Figure 35	Oscillating Stylus System - Block Diagram	84
Figure 36	'Surface Quality Comparator' System	86
Figure 37	'Flying Light-spot' Surface Inspection System	86
Figure 38	Basic laser interferometer	90
Figure 39	Interference Fringes	90
Figure 40	Automatic Threshold Control	94

SURFACE FINISH MEASUREMENT
FOR ADAPTIVE NUMERICAL CONTROL OF MACHINE TOOLS

Dipak Basu

ABSTRACT

Evaluating surface finish in order to determine the quality of work is a practice that has been with us ever since the first tool was invented. But measuring surface finish based on modern surface metrology is of fairly recent origin. Even more recent is the technique of measurement and control of surface finish by automatic means, as required by adaptive numerical control of machine tools. Modern technology has provided the means for fast production of complex machine parts of superior quality at minimum cost, and research is continuing for further improvement. Surface finish measurement, as the ultimate quality control tool, has to keep up with the technological changes that are being constantly introduced to machine tools and their control systems.

In this report, a survey of the present state of the art of surface finish measurement and control is made. In order to understand the environment in which surface finish measurement systems are expected to perform, a brief and general review of metal machining systems, numerical control and adaptive control is provided.

ACKNOWLEDGEMENT

I am grateful to Dr.S.Gracoversky for his guidance, suggestions and encouragement in preparation of this report.

I also thank Dr.V.Ramachandran for his assistance and guidance in completing this work.

I admit a particular debt of gratitude to the professors of the Electrical Engineering Department through whose teaching I have greatly enhanced my understanding of modern control technology.

CHAPTER I

INTRODUCTION

During the last two decades, metal machining techniques have achieved spectacular progress, mainly as a result of rapid advancement in Numerical Control systems. Ever increasing sophistication of the machining process has kept challenging control technology with intriguing problems. Although steady growth of solid state control and computer technology has helped solve many of these problems, the metalworking process has proved to be far more complex than hitherto realized.

Adaptive control, that is, control action to compensate for undesirable changes in certain parameters affecting the quality of work by using on-line information regarding tool action during the machining process has always been entirely dependent upon the skill of the operator. Automatic control techniques used to be either open-loop, or closed-loop with reference to fixed set-points. When it was realized that fixed mathematical descriptions of the many interactive processes would not be able to provide the ideal control actions, a frantic search for necessary devices for adaptive control of machine tools was launched. Problems in several areas were encountered, foremost amongst which was absence of adequate on-line measuring instruments. Difficulty in providing scientific description of many of the process variables was another problem. While some success was achieved in adaptive control of one or more individual control loops involving well-defined, measurable variables, it was a far cry from the total adaptive control that experts had envisioned. For one thing, well-defined variables are not independent, but interactive with other ill-defined and random variables, making metal machining a stochastic multivariable process.

Adaptive numerical control of machine tools is a closed-loop system wherein input program parameters are continuously and automatically optimized with the help of data obtained from actual on-line observation of several variables. The observation may range from simple sensing of reference values for ON-OFF operation to real-time, continuous measurement of values, curve shapes and functions and instantaneously processing them to computable forms. Continuous input parameter optimization is necessary to meet certain specified objectives or performance criteria. A further sophistication is attempted when the need arises, by utilizing optimal control programs, which optimize certain input or control functions instead of a set of parameter values.

The principal goal of adaptive control is either sustaining the efficiency of the input program or improving upon it. In all types of machine tools, the input program consists of specifications of cutting speed, size of cut, tool material, tool shape, cutting fluids and similar information.

An adaptive control system would judge the suitability of such input information against certain primary objectives, namely, size, surface integrity, surface finish and minimum cost of the finished product. Continuous observation of these parameters is therefore essential for optimizing the process.

Many sensors and on-line measuring devices have been developed over the years for measuring and controlling size, insofar as fixed quantities like length or diameter are concerned. But suitable devices for accurate, direct measurement of complex, contoured shapes and taking rapid control actions are yet to be perfected.

Surface integrity, which refers to residual stresses, cracks, and other superficial surface characteristics that modify the functional properties of the work material is generally controlled by the input program only, since adequate on-line sensors are lacking.

Continuous surface finish measurement has gone through many stages of development, but a practical and reliable device is still lacking. As a result, its control is generally dependent upon error-prone stylus-probe contact devices or input data gathered from more accurate off-line observations.

It will be noticed, however, that all the above three parameters relate to the quality of the finished product and consequently their accurate control is of paramount importance to the machining process. Accurate control requires accurate on-line measurement. Conventional sensing devices, no matter how sophisticated, have proved ineffective, since they mostly involve contact with the workpiece and hence the measurement is subject to friction, vibration and other random disturbances. Research work has therefore been mainly directed toward non-contact electro-optical sensors to deal with accurate dimensions, surface integrity and surface finish.

Minimum or optimum cost which is related to production speed, is fairly well described in terms of several measurable variables. Its relationship with the above three performance criteria, however, is either based on fixed input data derived from shop experience or follows an appropriate search strategy programmed to optimize the operation. Obviously, improvement of sensing and measurement techniques will provide better cost control.

4

This technical report mainly reviews the latest methods of on-line surface finish measurement and demonstrates its importance to adaptive numerical control of machine tools.

The report has been organized to touch on all general aspects of numerically controlled machine tools in order to provide an understanding of the system environment within which the surface finish measurement and control apparatus is expected to perform.

Starting with a brief history of the development of adaptive numerical control of machine tools, the report continues with a physical description of the machining process and equipment, followed by a discussion on the variables associated with the process. The adaptive control system is described next, with special emphasis on surface finish control as an important tool in the overall system.

Having provided an adequate background of the system configuration, the report now goes into details of surface finish measurement techniques. First, the surface metrology or the measurement units and standards are discussed. Then, a statistical analysis of surface finish as a stochastic system is presented. Influence of secondary parameters, such as cutting forces, cutting power, cutting temperature, vibration and tool wear on surface finish quality is also treated briefly. Optimal control of cutting speed and feedrate with the help of continuous measurement of surface finish is also suggested. Finally, past and present measurement techniques and instruments are analyzed in the light of economics, accuracy and quality of the machining process.

In conclusion, the salient points of the report are summarized, achievements and shortcomings in surface measurement technology are mentioned and some guidelines on future research work are suggested.

CHAPTER 2

DEVELOPMENT OF ADAPTIVE NUMERICAL CONTROL

The first major research undertaking and subsequent development of automatic machining techniques were applied in the aerospace industry under government patronage during and after the second world war. Economic feasibility was not as important a consideration as the need for quick growth of the technology, which was destined to be a vital tool in implementing the "industrial revolution" that was just around the corner. Machine tool industry in general, therefore, called for the fullest capability of the control technology in order to develop an economically viable automatic control system.

The first generation of the control system, commercially introduced in 1954, was officially called "Numerical Control System" and consisted of vacuum tubes and analog circuitry.

A machine tool is said to be "numerically controlled" if it works in an automatic or semi-automatic manner according to instructions transmitted to it in a coded form. From a detailed drawing of the "part" to be machined, a "parts-program" is written. The program provides instructions on tool selection, feed rates, spindle speeds, machine axis motions, coolant control and other machine functions. The program is punched on paper tape or some other medium in a sequence corresponding to the desired machining sequence. The tape is fed into a "controller" or "processor" which takes over the operation by "reading" the instructions and activating the specified servo-drives and feedback systems. The program defines a part as a series of points, lines and curves in primary and

7

secondary coordinate systems. The capability of numerically controlled or NC machine tools, originally started with simple two-axis point-to-point positioning control of a drill machine, now ranges to more than 8-axis contouring control of multiple function machining centres producing complex shapes. Since the programming language is made up of a numerical code, the technique is called Numerical Control.

In 1959, the second generation NC system started utilizing solid-state technology with digital circuitry having individual transistors and discrete components. The logic elements were committed to printed circuit boards and the hardwired program was the wiring that interconnected these boards. Easy alteration of the backplane wiring provided a desirable degree of flexibility. But the expansion of control logic and increasing demands for new features rapidly made the size and cost of these systems prohibitive.

Integrated circuits (IC's) brought on the third generation in 1965, and solved the problems of size and cost. The small size of IC's, however, permitted more logic elements to be mounted on a printed circuit board. Interconnection of these elements moved from back-plane wiring to committed etched circuits, thereby introducing the first order of inflexibility. So much of the hardwired program was permanently etched on printed circuit boards that a user's changing needs generally called for complete redesign of the control system. It was of course possible to pre-engineer a degree of flexibility, provided the user could foresee exactly what changes he would make in future.

The fourth generation, software-structured, computer controlled NC systems, although conceived and applied as early as in 1964, did not receive immediate acclaim because of high cost. It was realized, however, that the system would restore to the user the flexibility of second generation NC's and active development work proceeded along with third generation NC's.

By 1970, minicomputers were economically viable, and the first softwired, Computerized Numerical Control systems (CNC) were commercially available. CNC generally utilizes a minicomputer and memory which replace much of the fixed-logic circuitry of the hardwired NC's. This stored logic, together with stored computer instructions, is called an application software program. The program permits flexibility in a machine tool, basically without changes in physical wiring or hardware. The facility of changing the operations of CNC after original manufacture is its biggest advantage over hardwired NC. This advantage of course comes for a price.

Consequently both hardwired NC's and softwired CNC's have gained acceptance for specific applications where the inherent advantages of each system can be economically utilized. Size of the machine tool installation and its desired capabilities are major considerations for selection of NC or CNC.

One of the immediate results of CNC development was a concept called DNC or direct numerical control. DNC is a system connecting a set of numerically controlled machines to a common memory for parts-program or machine-program storage with provision for on-demand distribution of data to be machined.

Typically, additional capabilities for collection, display or editing of parts-programs, operator instructions, or data related to NC process are provided.

The next step, being suggested by experts at technical conventions, will probably be DFC or direct factory control. Attaching a DNC system to a business computer.

By-products of CNC development are two very ambitious concepts which envisage use of computer as a powerful tool for all phases of metalworking. These are computer-aided design (CAD) and computer aided manufacturing (CAM). Although some form of CAD and CAM have been practiced in design and manufacturing for several years, the totally-integrated computer-controlled system is still not a reality.

In the late sixties, adaptive control emerged as a powerful tool of CAM. Considerable work has been done in this area since the introduction of CNC, but its widespread application is still a few years away. Originally developed for, and applied to milling machines, adaptive control was also used on several other simple machines with some success.

The primary objective of adaptive control is to continuously sense the cutting environment and provide an automatic means of continually adjusting the speed and feed of a machine tool for producing an acceptable machined part at the lowest cost. Actual production histories show that metal removal rates can be increased 30-80% using adaptive control, even in its present state of development.

With proper optimization of cutter paths and machining sequences to take full advantage of adaptive control, even greater metal removal rate improvement can be achieved. The areas which require further experience and development for adaptive control can be broadly classified as follows: -

1. Development of suitable sensing devices for direct measurement and control of primary performance criteria, such as size, surface integrity and surface finish.
2. Obtaining data on the influence of secondary parameters such as, cutting force, cutting power, cutting temperature, vibration and tool wear on the above performance criteria.
3. Development of suitable sensing devices for detecting significant deviations in the parameters which are dependent upon the properties of tool and work materials.
4. Obtaining sufficient information on the natural scatter of existing data on variables which are random in nature.
5. Development of improved sensors together with compatible controllers and fast response actuators for the tool-workpiece contact area, with particular attention to temperature distribution, vibration, tool tip plasticity, tool positioning and automatic tool changing.

It is recognized throughout the industry, however, that to apply adaptive control in the most efficient manner, the total economics of the system must be known. An economic balance exists between the ideal goal of absolute maximum machining rates and supportive costs incurred to achieve that goal. The following curve shows an approximate relationship. (Fig. 1.)

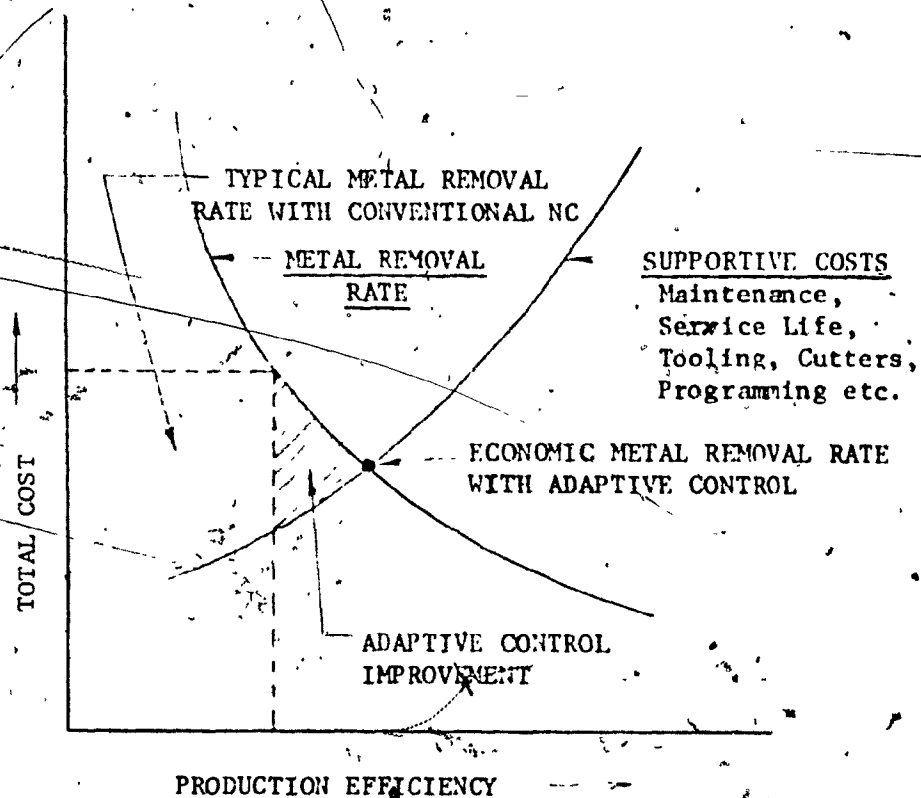


FIGURE 1. COST-EFFICIENCY RELATIONSHIP WITH OR WITHOUT ADAPTIVE CONTROL (8)

The exact location of the point of balance will depend upon the type of industry, the extent of diversification of products, size of installation, rigidity of the control hierarchy and so on.

Present trends in control seem to lean more and more towards hierarchical DNC of one form or another. This provides flexibility, cost savings and optimum utilization. It is also true that more than two-thirds of the NC systems currently in the North American market are hardwired. The main reason is cost, since for simpler applications, hardwired NC is still cheaper. The economical cross-over point between NC and CNC is, however, moving steadily down and as each new development in micro-electronics is incorporated by computer manufacturers and these, in turn are applied to CNC's.

What may turn out to be the most significant step in this direction, is the recent commercial introduction of micro-computers by several small computer manufacturers. Heart of a typical micro-computer is a central processor of a single LSI (large-scale integrated) chip that measures 0.16" x 0.16". On this chip there are 2000 gates, the equivalent of some 4000-5000 transistors. In its minimum configuration, a complete micro-computer is mounted on a single PCB. In addition to the processor, the board also mounts over 2K of 8-bit core memory, provides direct access to storage memory stacks of 32-64K, and has all the hardware to make a full-fledged, though small, computer. There are quite a few micro-computers now available in the market with varied architecture and attractive capabilities. There is no reason why CNC manufacturers will not look into these in real earnest to bring down the cost and help the users create an effective and efficient DNC hierarchy.

While advancement in all areas of adaptive control is expected in the near future, it is encouraging to know that the peripheral technology is already prepared for it.

CHAPTER 3

NUMERICALLY CONTROLLED MACHINE TOOL

A PHYSICAL DESCRIPTION

3.1. General Comments

The magnitude of numerical control's impact on manufacturing technology is exemplified by the virtual revolution it has prompted in the design of machine tools, - an industry that used to be conservative and resistant to change. The nature of automatic control has made demands on mechanical design for greater precision and accuracy, improved part and tool handling, lubrication and cooling systems, and structural rigidity. New drive concepts have been developed for proper responding to electronic control signals. Elimination of operator manipulation has obviated need for handwheels and levers, thus greatly influencing machine configuration, which stood substantially unchanged for many years.

Precision and accuracy are inherent characteristics of a modern NC machine tool working with virtually no operator intervention. Consequently, greater machine precision is transferable to the machine tool with numerical control.

Machine vibration and tool chatter take on special significance with NC because of greater range of speeds and feeds used. This puts heavy demands on the rigidity of the machine structure and design of damping systems.

A great many sophisticated mechanisms and devices have been developed for part and tool handling. Essentially, numerical control allows free choice of parts and selection of operations to be performed.

3.2 Machining Systems

Numerical control, when it appeared in 1942, was developed to solve the problems of contour milling. It was next applied to drilling and reaming. With very few exceptions, the industrial application of NC was limited almost exclusively for 20 years to these two modes of operation. In the sixties, NC application expanded into diverse machine tool architecture, covering almost all kinds of machining operations.

The main features of machine tool control are related to two basic techniques:- Point-to-point or positioning, and contouring.

Consider a simple numerically controlled column drilling machine as example, (Figure 2). There are basically four moving parts in the machine: a table to hold the workpiece, which moves horizontally on one axis, a saddle to hold the table, which also moves horizontally on another axis, a drilling head that slides vertically on a column, and the drill itself.

On completion of a drilling operation, the drilling head is returned to its raised position. Before performing another work cycle, the table must be moved to a new position defined by a pair of Cartesian co-ordinates. This displacement is produced by the movement of the table on the saddle, and of the saddle on the frame. The two movements are independent and the form of the trajectory from one position to another is of no importance. When both these displacements are completed, the tool performs its work, combining a rotation about its axis with a series of translations parallel to its axis, in sequence, corresponding respectively to the stages of fast traverse, work feed and rapid return. This is an example of point-to-point or positioning system.

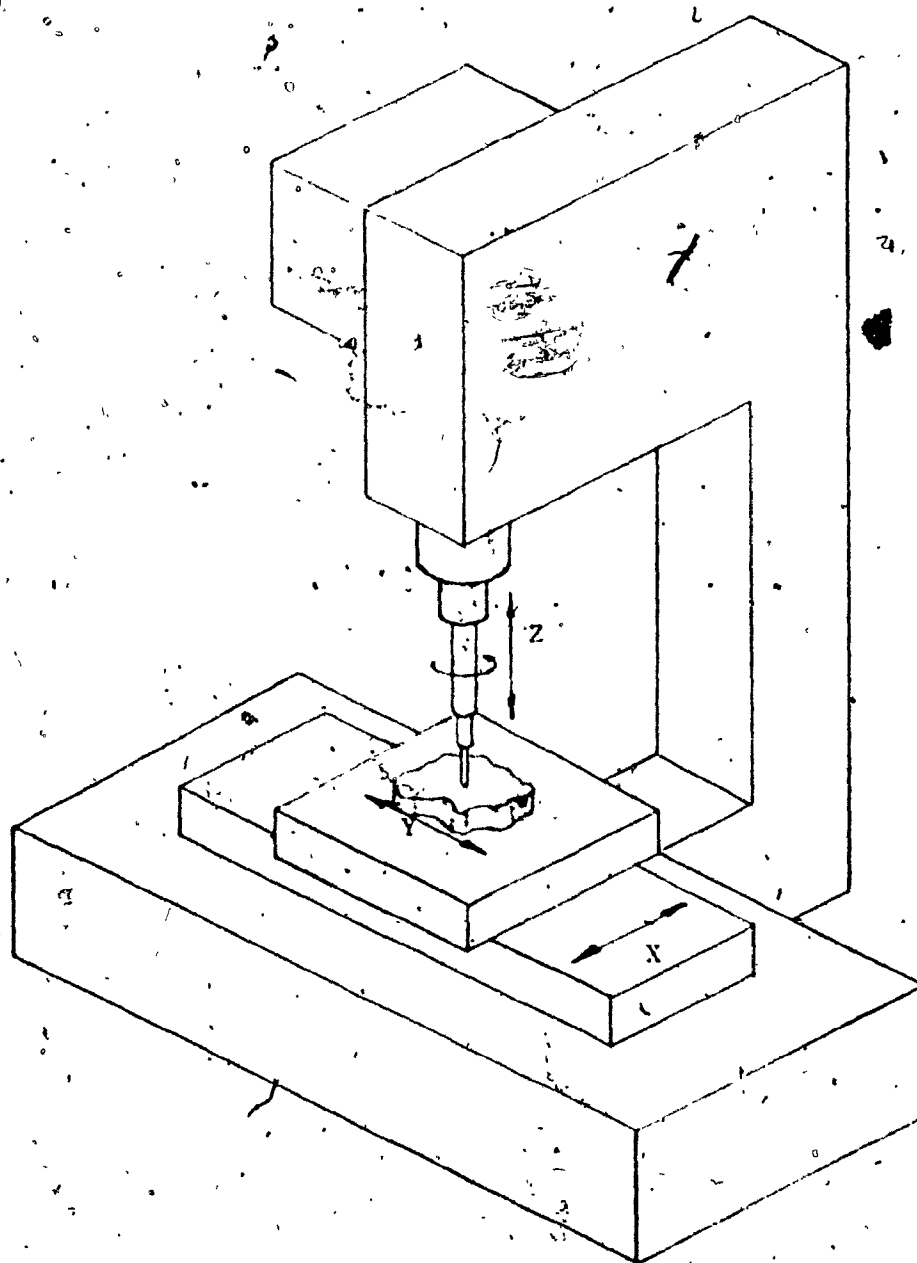


FIGURE 2. MOVEMENTS OF A DRILLING MACHINE

Positioning systems also permit certain machining operations (such as straight-cut milling) to be performed during axis movement. However, in these cases, the machining is done either in straight lines parallel to the axis moved or in a substantially random path between programmed points.

In contouring systems, which are also known as continuous-path systems, parts are to be machined in irregular or curved shapes. The workpiece or tool movements must be in a prescribed path continuously under control, thus requiring complicated co-ordination of the movements of the various axes. Every point in the continuous path describing the part shape must be accounted for, whereas, in positioning, only the end points of a movement are explicitly defined. Consequently, not only the physical equipment, but also the input information for describing the part is more complex.

There are several different approaches for the path description in contouring work. Linear interpolation is used for simple machine functions, whereas more complex shapes utilize a combination of linear and circular or parabolic interpolation. The approximating curve segments are, however, not necessarily circular or parabolic, - they may be parts of any curve described by a second order equation. The path description, therefore, is accomplished by approximating the curve representative of the actual part shape by numerous short segments of easily definable straight lines or curves.

3.3 Components of a Machining System

3.3.1 General Information Flow

A numerically controlled machining system is made up of an input data preparation system, the machine tool, sensing devices and a control unit.

The general information flow in the system is shown in Figure 3.

3.3.2 Input Data

Information from standard engineering drawings is transferred to a program sheet together with instructions on the sequence of operations to be performed and dimensions to be achieved in their proper sequence. The dimensions and displacements are based generally on a three-dimensional system of Cartesian co-ordinates established by Electronic Industries Association.

According to the degree of automation, many other data are specified in the program such as spindle speed, feed rate, tool identification, coolant selection, work cycle (drilling, tapping, spot facing, etc.), interpolation routine, etc.

The input medium can be one of the following three types: -

- a) Punched cards
- b) Punched Tapes
- c) Magnetic Tapes

Punched cards are no longer a popular input medium because they are vulnerable to error in handling and contain data in very low density.

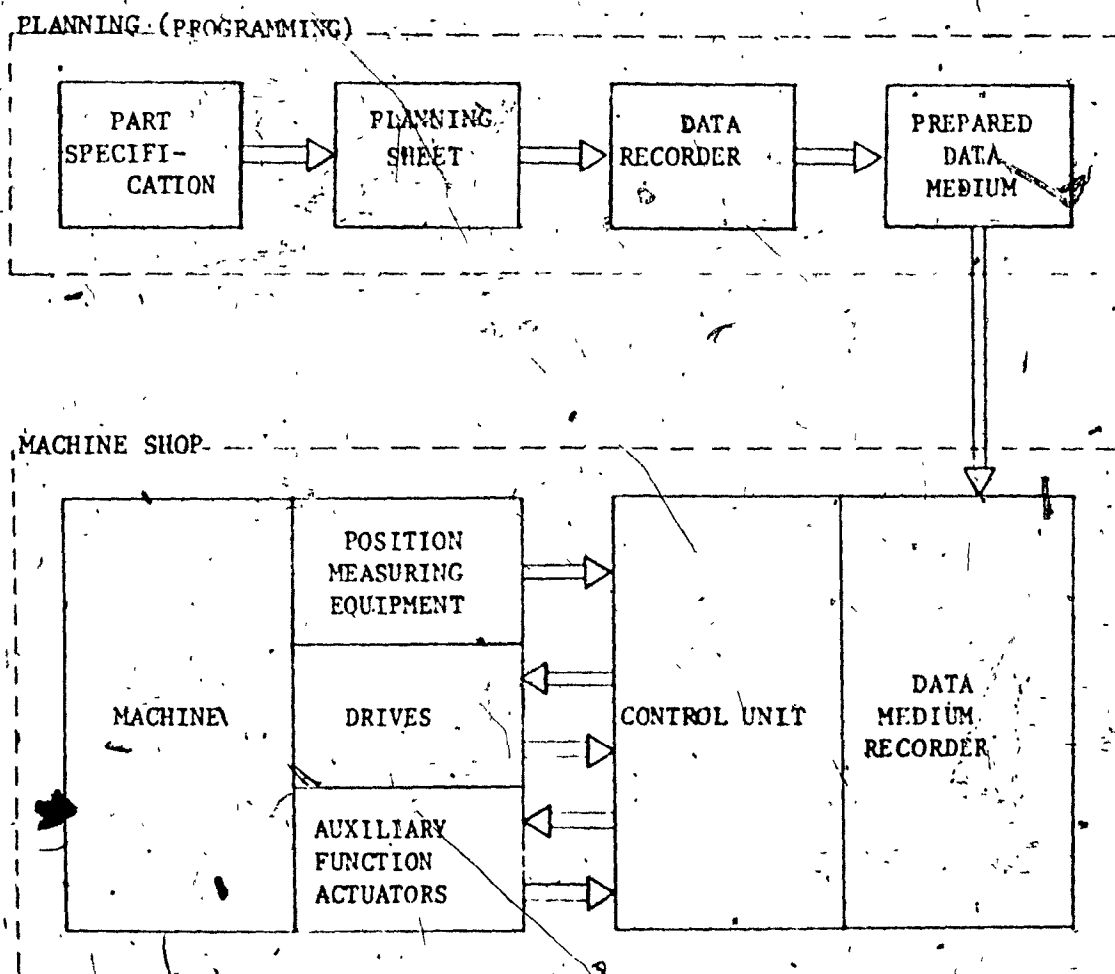


FIGURE 3. GENERAL INFORMATION FLOW

Punched tapes are most widely used since handling and processing are reasonably fast and inexpensive, data can be visually inspected and tape reading can be accomplished by mechanical, pneumatic or optical means.

Magnetic tapes have high data storage density and fast read/write rates. But accidental erasure of data can be a problem on shop floor and visual data inspection is impossible. However, complex contouring operations require a large amount of information, and since the speed of punched tape readers can limit the performance of the system, magnetic tapes are frequently used for such operations. Magnetic tapes are also used where extensive computer functions are performed.

3.3.3 The Machine Tool

Figure 3 described the flow of information between the machine tool and its control unit. Figure 4 describes in greater detail the interaction between the two.

The machine tool is equipped to perform automatically with the help of drives and auxiliary devices that respond to control signals. The mechanical means for automating a machine tool is a function of many variables. Consideration is given to the type of machine to be controlled, the degree of accuracy required, the versatility desired and overall system compatibility. In general, the aim is to exploit the machine's capability as much as possible without undue complication.

Movement of machine slides is effected either by a direct-coupled hydraulic piston drive, a rack and pinion assembly or a lead screw. Linear induction motors are in the development stage, but will soon command considerable attention as the best answer to precision linear drive problems.

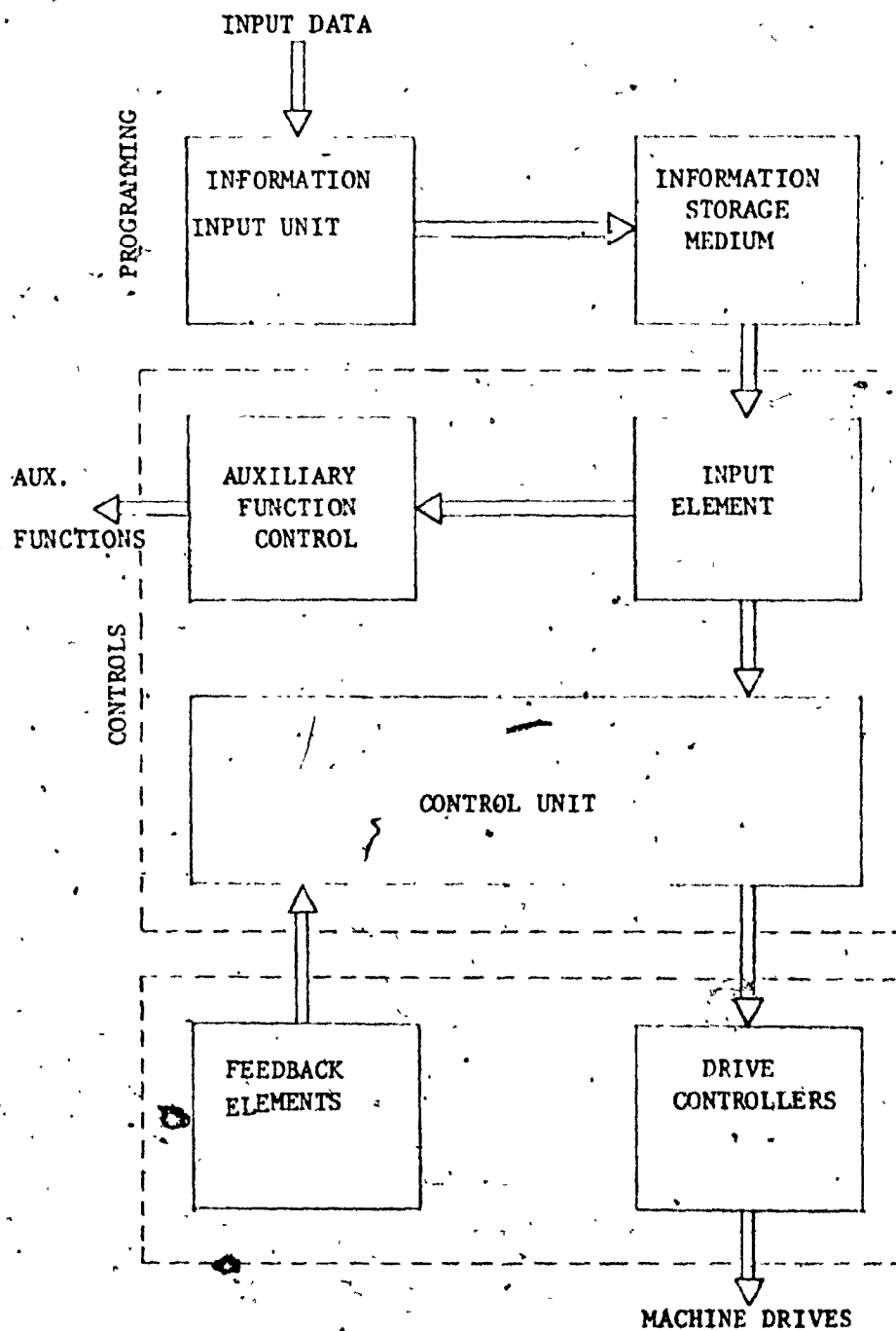


FIGURE 4. MACHINING SYSTEM - BLOCK DIAGRAM

Drives for rotating parts take many forms. The use of hydraulic, electric or pneumatic drives is dictated by the type, requirements and size of the machine and the type of control. Broadly, the following types of motors are utilized:-

- a) Linear Motors - Piston jacks driven by air or oil pressure.
- b) Rotary Motors - Squirrel-cage induction motors, Speed controlled a.c. or d.c. motors.
- c) Stepping Motors- Control signals direct the motor to rotate through a prescribed number of "steps" corresponding to a desired displacement.
- d) Hydraulic Motors- With constant displacement pistons.

3.3.4 Sensing Devices

Continuous on-line sensing of cutting environment is necessary in order to apply effective control to the system. Accurate sensors and transducers are therefore essential ingredients of a control system. While some fifty variables directly or indirectly influence the machining process, it is neither necessary, nor economically feasible to sense or measure all of them. It is sufficient to be able to provide scientific description of the relationships among all interacting variables, but no spectacular success has been achieved to this end. Consequently, it has become absolutely essential to develop precision instruments to measure and control the vital parameters, so that empirical relationships used in the input program to describe the whole system generate a minimum number of errors.

Instrumentation technology has been more successful in development of some areas than others. In recent years, demands for greater accuracy has resulted in

development of non-contact electro-optical measuring devices utilizing the latest optical and laser technology. The trend is towards more and more error-free data collection for compatibility with modern control systems.

Following is a list of the more important of the machine variables and corresponding sensors:-

<u>VARIABLE</u>	<u>SENSOR</u>
Tool or Part position, Tool Wear, Size	Direct-coupled linear or rotary position transducer, Magnetic or Electrostatic Detector gauges, Stylus-probe electronic gauge, Photo-electric Sensors, Electro-optical Sensor, Laser Interferometry, Magnetic air-gap sensor, Pulsed LED.
Surface Integrity	Laser holograph(36), Scanning Electron Microscope (25,38)
Surface Finish	Stylus-probe, electro-mechanical profile recording systems, Electro-optical sensors, Laser Diffractometer (21), Laser interferometry, Laser "flying light-spot" system (16) Holographic Interferometry.
Spindle Speed	Tachometer, Hall-generator, Electromagnetic non-contact system (37)

<u>VARIABLE</u>	<u>SENSOR</u>
Spindle Torque	Strain gauges, Dynamometer.
Spindle HP, Cutting Forces	Electromagnetic non-contact system, Piezo-electric crystals.
Vibration and Chatter	Crystal Accelerometer, Displacement-sensing optical device, Inductive a.c. bridge, Seismic pick-up, Relative Velocity-pick up.
Tool Workpiece temperature	Tool-work thermocouple effect, Embedded or Contact thermocouple, Tool holder thermocouple, Tool holder thermocouple, Resistance Bridge, R.T.D., Thermaistor.

3.3.5 Control

Fully automatic operation of a NC machine tool consists of three basic phases - input data reading, controlling, position monitoring.

The main function of the central unit is information processing. A peripheral part of this function is receiving signals from the tape reader, determining their proper sequence and transmitting commands to corresponding actuators.

The more important information processing work is associated with dimensional data from slide movements. Controls interpret output signals from the tape reader, and feed-back signals from the machine, and transmit commands to drive systems after processing the information. In modern control systems, data processing and calculations are assigned to computers. Control logic for actuation of drives is

performed by solid-state programmable controllers which are gradually replacing conventional electromagnetic relay logic systems.

Programmable controllers or PC's have begun to play an increasingly important role within the machine control/computer control hierarchy, because they are better suited than relay systems for data communication with computer under any system configuration. PC is really a special-purpose digital computer with control level I/O interface. Given the proper response characteristics, it can be used wherever a sequential digital process is to be controlled.

Many control configurations are in use, but the most popular structure is shown below through a generalized diagram: (Figure 5).

The system is simple and flexible, and designed with the popular building block approach. All the modules are software implemented. Positioning and contouring controls can both be achieved to any degree of complexity. Core memory, storage capacity, tape reader speed, control program capability and controller versatility will naturally depend upon the performance criteria of the machine tool. Irrespective of the size of a system, its trend is towards compatibility with the totally integrated design and manufacturing system of the future. (CAD/CAM).

3.4 Machine Tool Types

Single function NC machine tools are available broadly for the following machining functions: -

Turning	-	Mainly lathes, which are also used for
Boring	-	boring, thread-cutting, knurling, cutting
Drilling	-	Vertical or horizontal drilling machines,
	-	gun drills, tapping, punching, reaming.
Broaching	-	
Punching, Shearing	-	
Milling, Shaping	-	
Grinding	-	
Welding	-	Continuous or spot-welding.

Multi-function machine tools or machining centres are direct results of numerical control development. They are available in three to twelve axis arrangement, with automatic tool changer for more than hundred tools of different sizes, shapes and types. Depending on the production quantities, machining centres may or may not be economically feasible. An attractive alternative is the flexibility of combining several single-function machine tools with an automated transfer machine.

CHAPTER 4

MACHINING PROCESS VARIABLES

The metal machining process, like most physical, industrial and biological processes, may be considered a multivariable process. Interactions exist among the variables, and they have a significant effect on the performance of the process. It is therefore worthwhile examining the behaviour of these variables in the metalcutting environment(6).

As mentioned in Chapter 1, the primary variables giving the performance criteria are: -

- 1) Dimensions
- 2) Surface Integrity
- 3) Surface Finish
- 4) Production Rate or Cost

One of the basic empirical relationships governing the metalcutting operation is given by the following equation, - sometimes known as Taylor equation: -

$$VT^n = \frac{K}{f^a \cdot d^b} \quad \dots\dots (4.1)$$

Where

V = Cutting Speed

T = Tool life

f = Cut Thickness (Feed)

d = Cut Width (or depth in turning, drill radius, tooth engagement length in milling, etc.)

(f.d. = Cross-sectional area of the cut)

K = Proportionality constant dependent upon materials

a, b, n = Exponents dependent upon tool and work material properties.

From the above equation, an expression for optimum tool life has been derived:

$$T_o = \frac{(1-n)}{n} R \quad \dots (4.2)$$

Where

R = Operating factor, i.e.

Tool changing time (for maximum productivity)

Tool cost per tool change

or, $\frac{\text{Tool cost per tool change}}{\text{Elapsed time cost per unit time}}$ (for minimum cost)

Partial differentiation of equation 4.1 with respect to the variables V, f and d will give optimum values of these variables as they relate either to production rate or unit cost. Since the exponents a and b are substantially less than 1, theoretically the efficiency of metal removal increases continuously as both feed f and cutting depth d are increased. But f and d are limited by other constraints and practical considerations.

Equations 4.1 and 4.2 can be combined and expressed in a different form as follows:-

$$\text{Optimum cutting speed } V_o = \frac{K \left(\frac{n}{1-n} \right)^n}{K^n f^a d^b} \quad \dots (4.3)$$

Optimum production rate $Q_o = 12 V_o f d$

$$= \frac{12K \left(\frac{n}{1-n} \right)^n f^{(1-a)} d^{(1-b)}}{K^n} \quad \dots (4.4)$$

Equation 4.3 presents an idealized basis for optimum cutting speed, but in order to implement an effective optimization routine, information from direct measurement of size, surface integrity and surface finish must be available.

The effects of control variables V , f and d on surface integrity and finish are mainly dependent upon tool and workpiece materials. Experimental data describing these relationships are available for various materials and cutting fluids (6). These data can be used for the purpose of input programming. The wide variations in the nature of surface finish with different material generally prove to be an inconvenient feature in modern NC programming. As a result, the control strategy has to utilize data from inefficient measurement techniques supported by generalized empirical relationships or by an appropriate optimal search program. Unfortunately, several other variables, - most notably vibration and chatter, also have pronounced influence on surface finish and most available control programs are inadequate to handle this.

Early adaptive control systems and most of the present ones, therefore, utilize information on the following secondary parameters, which happen to be comparatively more measurable: -

- (1) Cutting Forces
- (2) Cutting Power
- (3) Cutting Temperature
- (4) Tool Wear
- (5) Vibration

Measurement techniques for cutting forces, power and vibration have advanced to a reasonable degree of sophistication. There is, however, very little satisfactory information on dependent relationships between these quantities and control variables V , f and a , except from empirical data.

Direct measurement of tool wear rate is still in its infancy, but much work has been done in developing relationships between tool wear and other measurable variables.

Cutting temperature has always received considerable attention as potentially the most useful feedback information, because well defined relationships do exist between tool wear mechanisms and tool-workpiece interface temperatures.

The following equation, due to Shaw (12) is largely representative of a number of descriptions reached by theoretical or experimental analysis:

$$\theta \propto u \left(\frac{Vf}{kC_v} \right)^{0.5} \quad \dots (4.5)$$

Where

- θ = Absolute temperature
- u = Cutting energy per unit volume
- V = Cutting Speed
- f = Cutting thickness or feed
- k = Coefficient of thermal conductivity
- C_v = Volume specific heat

Since values of K and C_v can vary widely with different materials and may in fact be impossible to determine for certain combinations of tool and workpiece materials, the exponent .5 may have to be adjusted experimentally.

Shaw suggests that practical use of the above equation is limited to only high cutting speeds where u remains virtually constant, giving a modified simpler relationship: -

$$a \propto v^{0.5} f^{0.3} \dots (4.6)$$

where the modified exponent of f signifies that at high speeds, lower unit energy is required for the same feed.

The mechanism of tool wear rate has been found to be analogous to chemical rate processes (6), as demonstrated by the equation 4.7

$$T = Ae^{E/\theta} \dots (4.7)$$

where

- T = Tool life
- A, B = Constants
- θ = Absolute temperature

Experimental results have indicated that the above equation holds good only within certain temperature and cutting speed threshold. Extensive analyses of temperature distribution at the tool-workpiece interfaces have been performed, mainly with the help of embedded thermocouple measurements. While it has been established beyond doubt that there are fundamental reasons why cutting temperature

should significantly influence tool wear, it is also clear that these relationships are extremely complex and hard to describe.

Fig. 6 gives a set of qualitative curves on rate of tool wear versus cutting temperature for five distinct manifestations of tool wear as suggested by Vieregge (6).

For practical purposes, and also for potential application in adaptive control, it has been suggested that wear mechanisms (a), (b) and (c) in Fig. 6 be combined and treated as insensitive to temperature but sensitive to cutting forces or pressures. Similarly (d) and (e) should be combined as a single mechanism dependant solely upon cutting temperature.

Advanced instruments for continuous measurement of temperature at the tool-workpiece interface have been developed for laboratory work, but their extensive practical utilization has lagged behind. Following is a list of temperature measuring devices currently in use or being developed for machine tool application:

Tool-embedded Thermocouple - Much experience, strong signal at high temperatures, instability, insulation failure, slow response.

Resistance Temperature Detector (R.T.D.)

- Strong signal at all temperatures, low temperature range, very slow response.

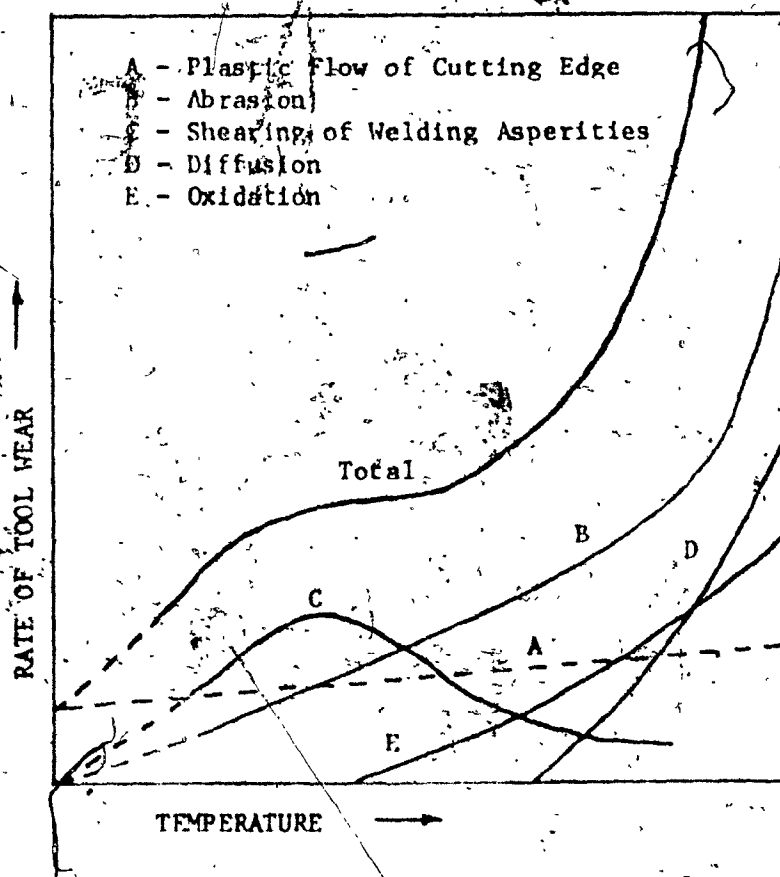


FIGURE 6. RATE OF TOOL WEAR VS. TEMPERATURE (6)

Thermistor

- Strong, stable signal, fast response, low temperature range.

Tool and Workpiece used as T.C. materials

- Holds much promise, successfully used in actual application, not enough data on various combinations.

Vibration of machine tools has a pronounced effect on the quality of surface finish. Advancement in machine tool design due to introduction of adaptive numerical control has pushed the machines to the limits of their mechanical and structural capability. Higher speeds, increased feedrates and cutting depths require greater cutting forces and power, and result in increased vibration and chatter. Vibration analysis is therefore of increasing concern to machine tool designers, and is already reshaping the operation and design of machining systems.

Unlike other parameters, vibration and chatter are entirely harmful. Tool life is drastically reduced by cuts that involve excessive vibration. Surface roughness limits are easily exceeded when vibration and chatter set in. Vital machine components, such as, drive trains, spindle bearings and slideways are adversely affected by vibration.

Vibration in machine tools is basically of two types: -

- (1) Forced (2) Self-excited.

Forced vibrations are caused by moving or rotating sources located either within the machine itself or outside, but connected to the machine through foundations and building structures.

Typical internal forced vibration sources are cutter impacts, drive irregularities, spindle unbalance or noisy servo-control performance.

Self-excited vibration is due to basic instability of the system or process. In machining process, this form of vibration causes chatter. The instability results from a combination or interaction of the metal removal process and the structural deflections or dynamics of the machine tool. The instability initially has no vibration forces associated with it, but such forces build up over a period of time as demonstrated through the closed-loop diagram in Figure 7.

For further understanding of chatter, let us look at Figure 8, which shows the cutting operation in a lathe. The actual chip thickness being cut, or the feedrate is affected by machine deflection and also by material left on the surface from the previous revolution. In effect, the workpiece "records" the vibration and "plays" it back one revolution later. This forms the feedback or regenerative path for the vibration and leads to the instability we call chatter(23,24).

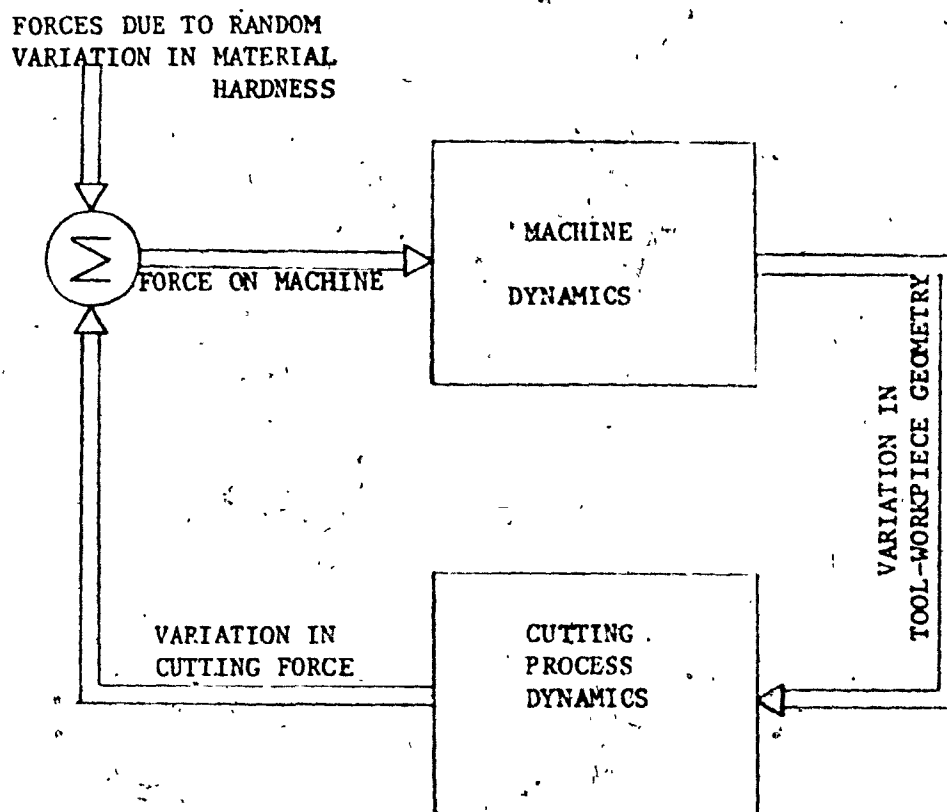


FIGURE 7. BUILD-UP OF CHATTER

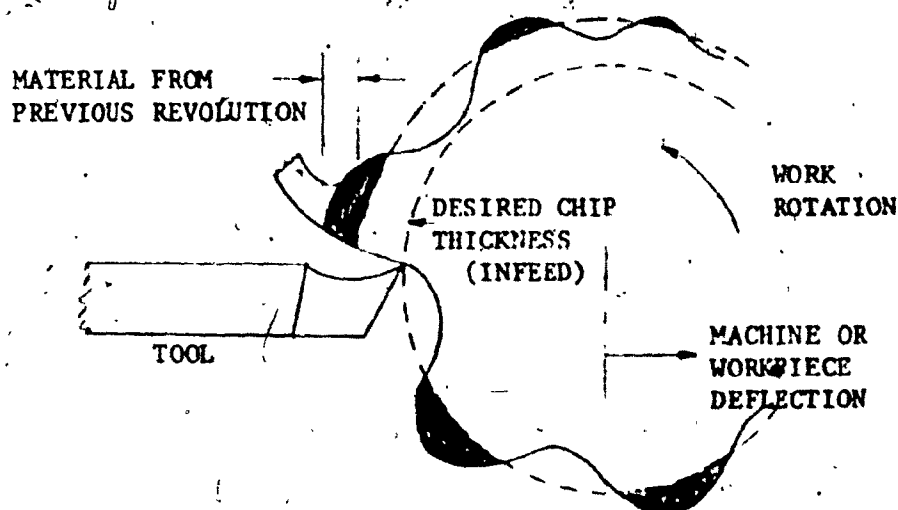


FIGURE 8. EFFECT OF MACHINE DEFLECTION ON CHIP THICKNESS (23)

The cutting force generated during chip removal has been found to be a function of the feed. The workpiece material, tool geometry and depth of cut also greatly affect the cutting force. All these factors have been brought together into a term called cutting stiffness.

The relationship of feed, cutting stiffness and machine dynamics is shown in Figure 9, which is really an extension of Figure 7 in concept.

Many of the causes of vibration and chatter can be eliminated at the design stage by modern modelling techniques and later with the help of dynamic testing programs. But self-excited chatter may require instantaneous adjustment of tool position and tool geometry in addition to the usual modification of cutting speed, feed and cut depth.

Considerable research work has been done on vibration and chatter and their effect on machine tool performance. Although study of machine-tool dynamics is beyond the scope of this report, its relevance to any study of surface finish measurement and control cannot be denied. Without going into any complex vibration analysis, it can be said that suitable techniques for vibration control is essential for optimum machine performance. The full range of feedback loops available for vibration control is immense due to interaction of the cutting process, drive trains, frame, bearings, tool and table positioning devices together with the fact that vibration is an erratic phenomenon and has to be handled as a stochastic process.

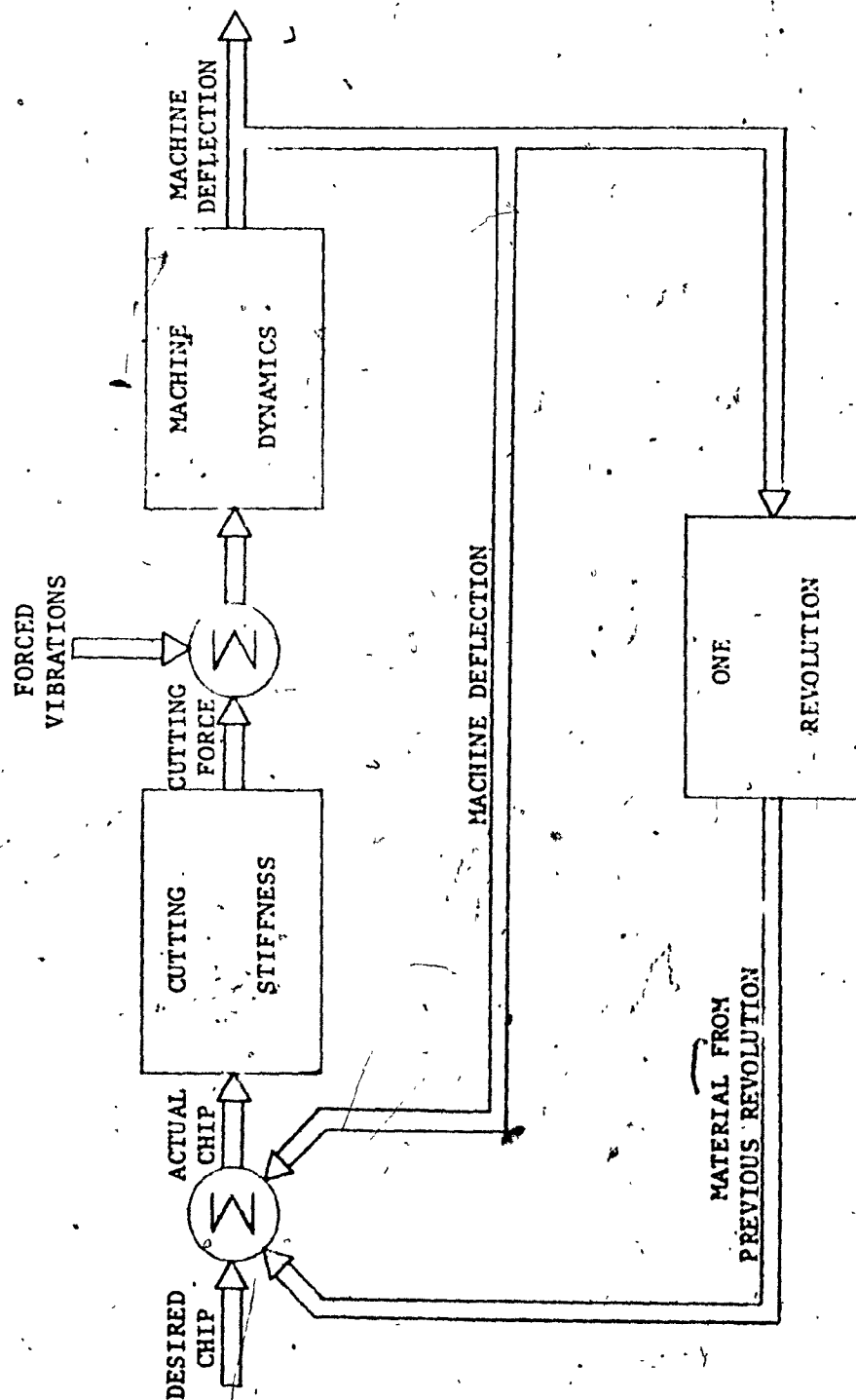


FIGURE 9. SELF-EXCITED CHATTER BUILD-UP

Cutting forces, torque and power are traditionally measured with dynamometers, strain gauges, piezo-electric crystals etc. Recently, non-contact measuring devices have been introduced commercially, which utilize the technique of inductive and capacitive coupling between stationary and rotating electromagnetic or electronic modules, transducing and amplifying the required analog signals with the help of the latest equipment in microcircuitry (37). Speed measurement is also incorporated in the same system.

Vibration measurement is essentially sensing of relative displacement between tool and workpiece. Accurate measurement, estimation and control of this relative displacement is absolutely necessary to achieve the machine performance criteria. Although conventional accelerometers are extensively used, the trend is towards non-contact electro-optical or electromagnetic devices.

CHAPTER 5

ADAPTIVE CONTROL TECHNIQUES

5.1 Theory

Adaptive Control systems are probabilistic decision processes in which there is some uncertainty that can be reduced during the course of the process by information derived from observation of the performance of the process.

In case of stochastic processes, the functions describing the problem have known probability distributions, but nothing can be done to reduce the uncertainty about future values of the probability densities. In adaptive processes, the probability distributions are not known in advance, but can be estimated by a "learning" procedure based on observation of the process.

The dynamic programming equations can be derived and solved only for problems where the uncertainty to which the process is to "adapt" can be completely specified at every stage by a set of sufficient statistics.

Let us consider a dynamic system described by

$$C(k-1) = C(k) - hx(k) - w(k)$$

where h is an unknown constant with its value described by a probability density p and $w(k)$ is a random variable with a known probability density q .

Because there are two sources of uncertainty, h and $w(k)$, no amount of observation can give an exact determination of the value of either. However, since p and q are known, we get a revised probability density for h at each stage. In this way, we can develop a recursive relation for the optimal return function in terms of initial resources and the mean and standard

deviations of random variables x and w .

A complete mathematical analysis of adaptive control is beyond the scope of this report, but the brief comments above will help in the appreciation of the practical applications described in the next few pages.

5.2 The Control System

In the previous chapters we have already introduced the basic concepts of adaptive control of machine tools. In essence, the art of adaptive control comprises two functions: performance measurement, or on-line determination of actual metalcutting performance; and control, or appropriate adjustment of cutting parameters to achieve the desired performance.

Figure 10 illustrates the capabilities of a fairly comprehensive adaptive control system developed by Bendix Corporation (22). However, depending on the type of machining operation, size, shape and material of workpiece and the degree of accuracy required, the system configuration may vary to a great extent. For example, the optimizing system may aim for only maximum cutting force or depth of cut under constant feedrate and spindle speed constraints. Operating conditions involving air gaps, interrupted cuts or continuous cuts are also sensed for rough-machining jobs in order to extend tool life and avoid unproductive cutting time. Positioning control for tool wear compensation often follows temperature signals and optical tool-wear measurements in the fundamental control loop. Several control schemes use an adaptive loop only for automatic vibration control in order to achieve a superior surface finish while the basic control loop handles

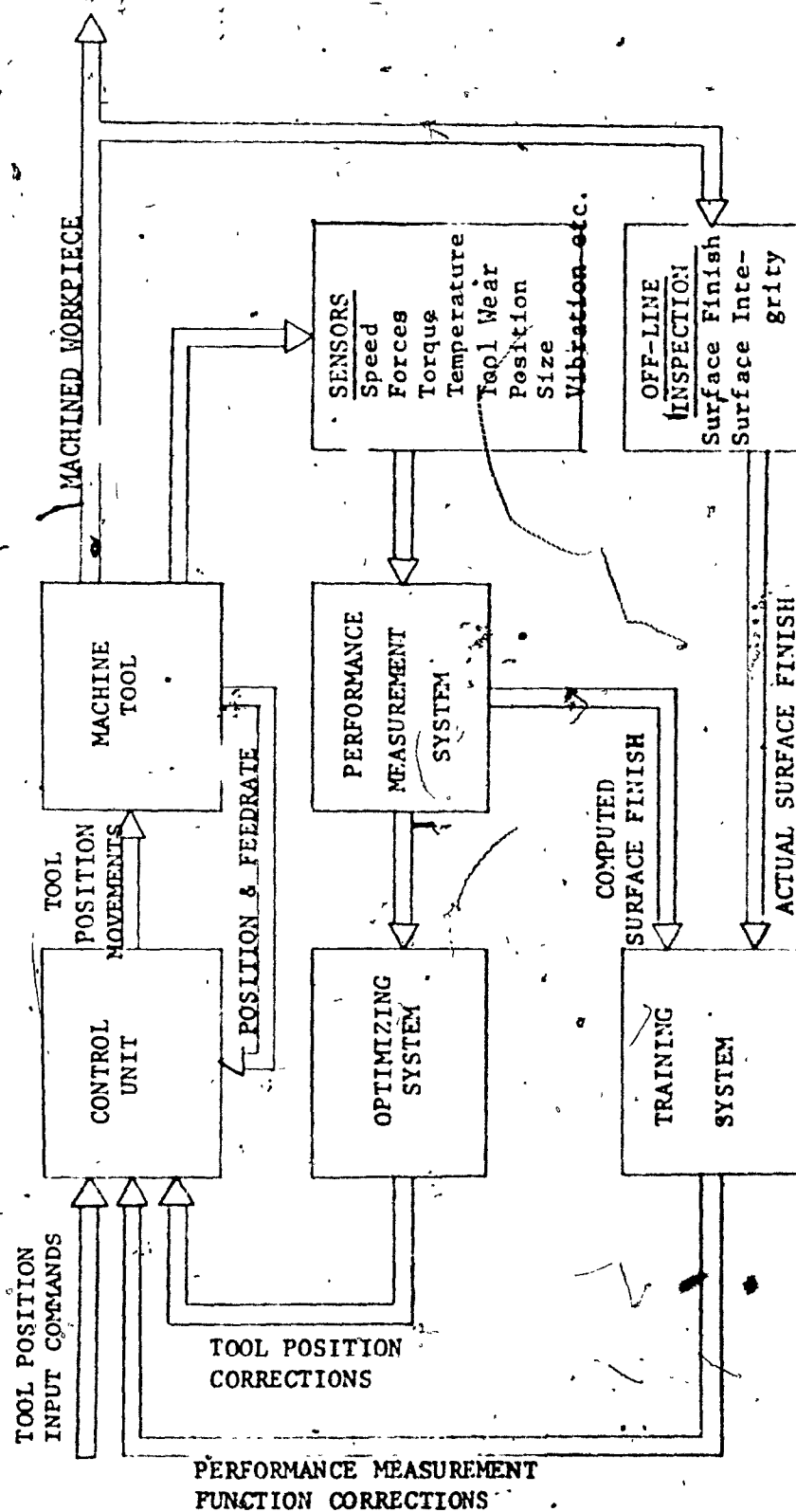


FIGURE 10. ADAPTIVE CONTROL SYSTEM
BLOCK DIAGRAM (22)

all other parameters by conventional numerical control.

Ideally, an adaptive control system employs three feedback control loops as the Bendix concept demonstrates in Figure 10. One is the conventional loop, which measures and controls the tool position and feedrates with the help of final input data on tool movements. This is basic numerical control.

The second loop is the adaptive loop, which measures how well the process is performing and then adjusts the controllable inputs for a better performance. Typically, the sensors determine on-line machine parameters such as spindle speed, cutting forces, torque, temperature, tool-wear, actual tool movement and vibration. A performance measurement system uses these measured parameters to compute a performance evaluation variable, which may be indicative of workpiece surface finish. The performance measurement system also details violations of preset constraint limits by the measured machining parameters, the calculated machining parameters (e.g., horse power) and the performance evaluation variable. Lastly, the performance measurement system determines the performance index, or how well the system is performing. The last two pieces of information are inputs to an optimizing system which employs a strategy that seeks to obtain better system performance within the limits imposed by the pre-set constraints.

The third one can be called a training loop, or a refinement loop, where the actual surface finish is measured. Two signals, the computed performance

evaluation variable and the actual surface finish measurement are inputs to a training system. The training system compares the two signals and computes corrections to the coefficients of the regression equations of the performance measurement system. The training system thus reduces the error between the predicted or calculated surface finish and the actual surface finish.

The performance index of the machining process is generally considered to be the metal removal rate, which is directly related to productivity and cost. For a description of the performance index optimization strategy, let us consider the operation of a grinder, whose main purpose is achieving a smooth surface finish.

The value of the metal removal rate for a single grinding stroke is the product of the table feed, cross feed and downfeed. Since, for a given layer the downfeed is held constant, it is sufficient to find the highest product of table feed and cross feed within preset constraints, in order to maximize the metal removal rate. To machine an entire surface, multiple strokes may be required. Optimization on a per stroke basis, therefore, does not necessarily lead to maximum productivity. At the end of each stroke there is some non-productive time during which the wheel must travel beyond the end of the workpiece before crossfeed can be permitted. For a given workpiece, the magnitude of the loss time or cycle time is proportional to the number of grinding strokes.

The strategy employed to optimize the performance index emphasizes the minimization of the number of grinding strokes. Table feed is reduced until parameter constraints are violated, at which time table feed is

increased. If it is reduced to its lower limit without violating any constraint, then the crossfeed is increased for the next stroke. By adaptive adjustments of table and crossfeed within pre-set constraints, most notably that of surface finish, the metal removal rate is maximized.

5.3 Hardware and Sensors

The hardware configuration for the above system is shown in generalized terms in Figure 11.

In the Bendix system the surface finish measurement system for the grinder was used off-line, but in a very effective manner. It may be more difficult to do so in case of other types of machine tools, but advanced on-line measurement techniques are being developed to solve this problem.

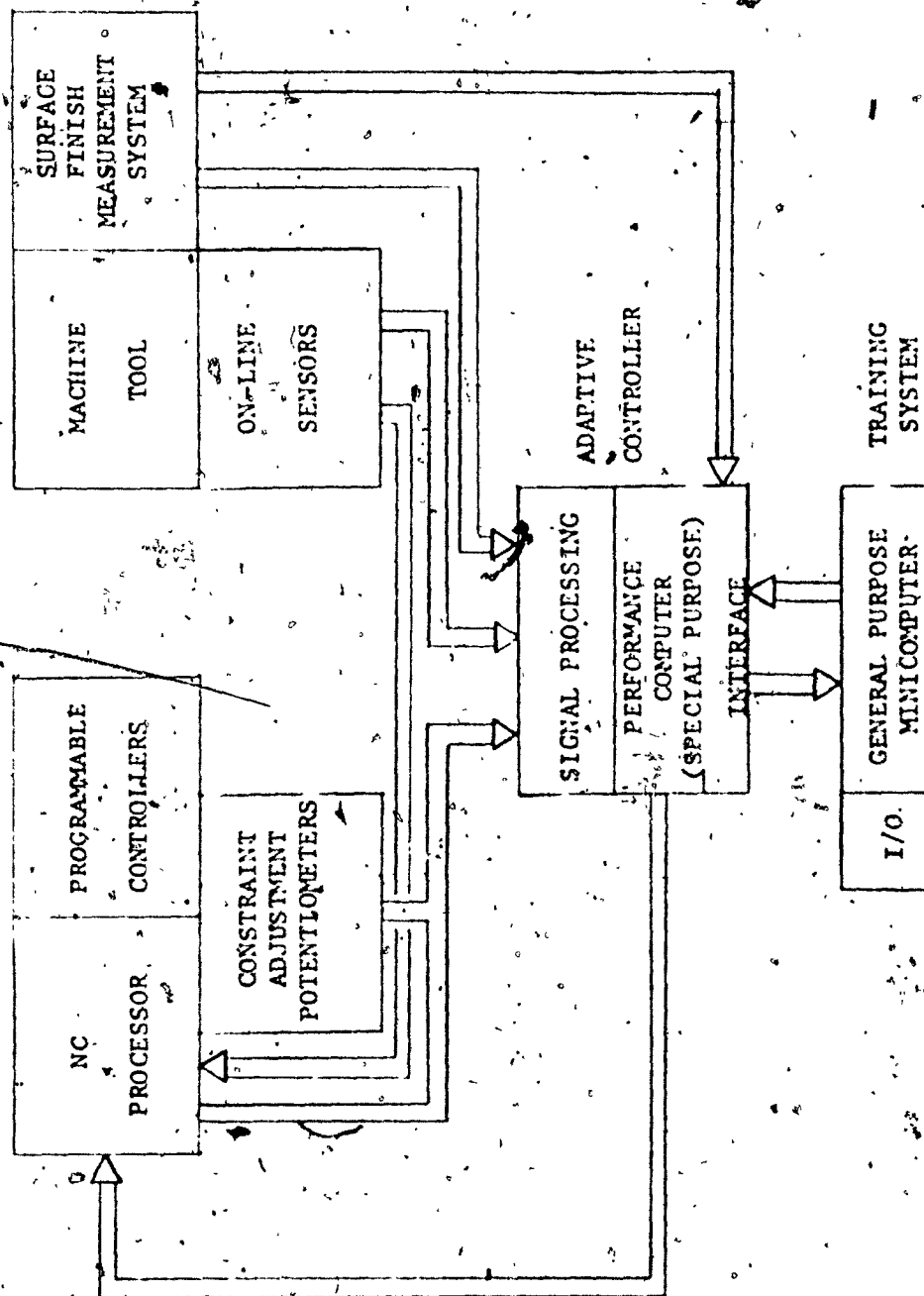


FIGURE 11. ADAPTIVE CONTROL SYSTEM
HARDWARE CONFIGURATION (22)

CHAPTER 6

SURFACE FINISH MEASUREMENT

6.1 Introduction

Surface Finish is a measure of the topography or geometry of the outer surface layer of a machined part. Lot of time and money are probably wasted on unnecessary finishing operations without obtaining the desired results to any degree of certainty. The trend is to "specify" and "control" all surface requirements of a component with the aim of arriving at an optimum surface topography - one that satisfies the cost/function relationship. It is a matter of value engineering. Ideally, we want to satisfy all the functional requirements with minimum effort.

Typical relationships of surface roughness to production time for commonly used tools and materials shown in Figure 12, are taken from British Standard BS1134, "Assessment of Surface Texture". The relationships clearly demonstrate that the quality of surface finish is dependent upon the type of machining. A typical preliminary visual analysis of the problem could go like this. The turning curve rises sharply at about $0.6 \mu\text{m}$. Grinding would probably do better. On the other hand, do we need $0.6 \mu\text{m}$?

Specification and control of surface finish of machined parts create other difficult problems due to the close relationship between the surface texture and the machining process itself. Further, the performance of the product in subsequent service depends on the characteristics of its surface. Besides production time or cost, other important factors related to surface

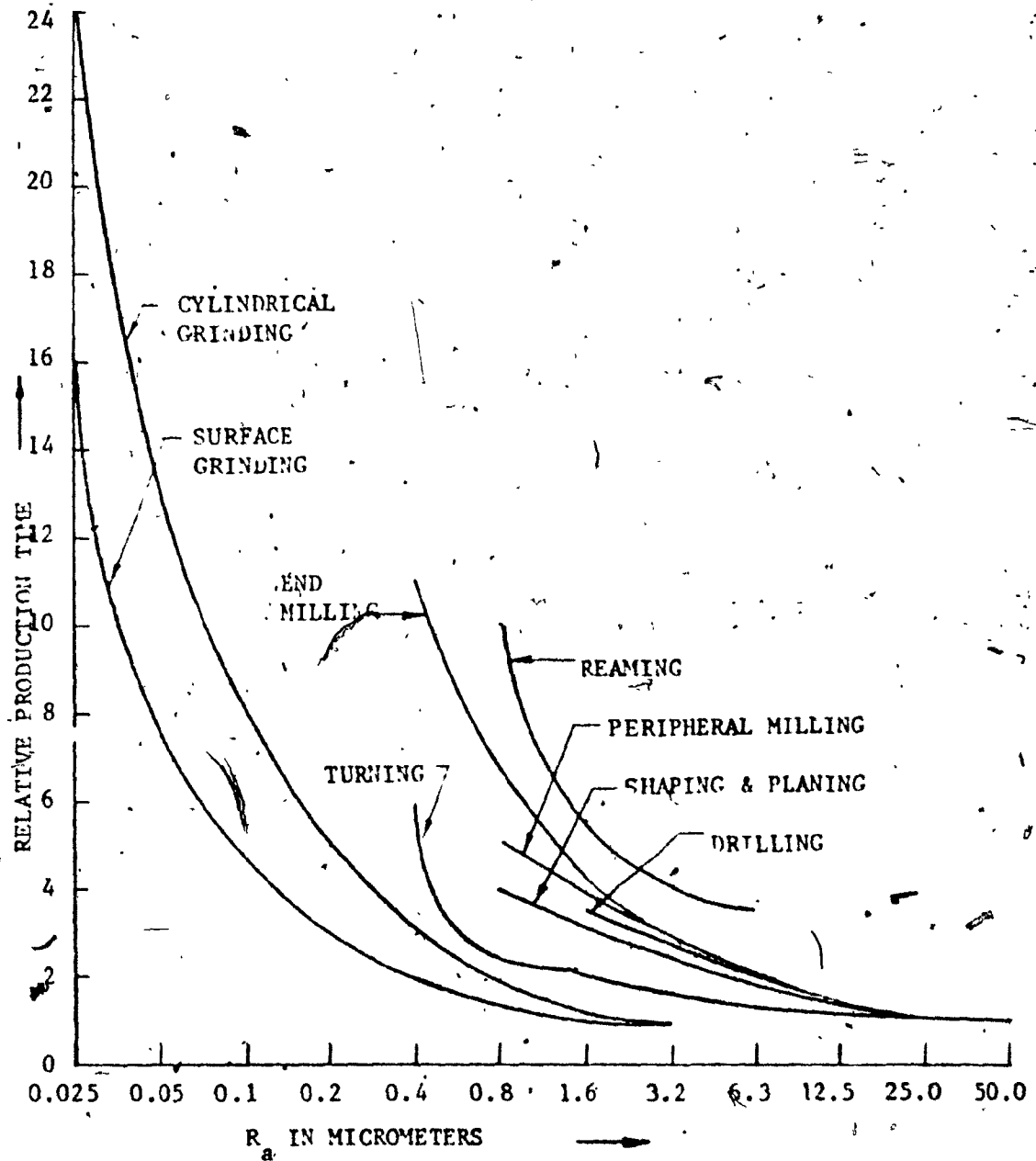


FIGURE 12. TYPICAL RELATIONSHIPS OF SURFACE ROUGHNESS TO PRODUCTION TIME (26)

are wear, fatigue strength, load capacity, rate of heat transfer, noise, bonding of paint lacquers and adhesives, and appearance.

Friction and wear depend to a large extent on the actual profile of two surfaces that are in sliding contact (19,20). The true area of contact is always considerably less than the apparent area because the surfaces only touch at those points where surface asperities meet. The actual stresses on the asperities, therefore, can be several times the stresses calculated for the apparent area.

The fatigue properties of a manufactured part are frequently influenced by the nature of the surface (19,20). The lubrication characteristics of a surface sometimes depend on the actual profile of the surface, since some contours do better at holding a lubricant than others (20). Stress corrosion is another problem associated with undesirable surface roughness (20,38).

Besides surface finish, there is another aspect of surface quality which must be controlled to ensure high reliability of the machined part, - surface integrity. Surface Integrity is a measure of metallurgical and mechanical alterations in the surface layer of the part.

In major industries, great emphasis is placed on providing guidelines for maintenance of high surface quality and especially, high surface integrity. The need for rigid control of surface integrity has increased continually in industries employing structural materials at higher and higher strength levels.

With increased strength levels, fatigue and stress corrosion resistance exhibit a marked increase in sensitivity to surface conditions (38).

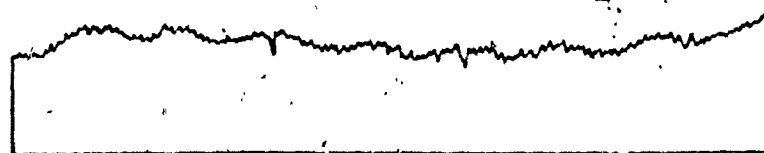
To maintain high surface integrity in chip removal operations such as milling, turning and drilling, machining conditions should be selected to provide long tool life. In addition, tools must be kept sharp (i.e., frequent tool change) to minimize metallurgical changes within the surface layer. In grinding, low wheel speeds and light down feeds, together with the use of highly active cutting oils, are necessary to minimize surface alterations. Post operative machining processes such as heat treatment, etc., and rigid inspection techniques are required to insure proper surface condition.

All these procedures increase the cost of manufacturing to unprofitable levels. Hence, adaptive control of surface quality with the aid of on-line measurements is essential for economical precision machining. Accurate on-line measurement techniques have not yet been perfected, but considerable work has been done in this area. A study of the measurement techniques requires a complete understanding of the standards and units of measurement used to describe the surface geometry.

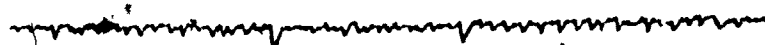
The surface texture irregularities consist of three superimposed components, namely roughness, waviness and form errors (Fig. 13).

6.2 Surface Metrology

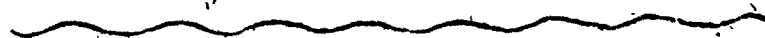
Metrology is the science of precise measurement. The aims of metrology are to provide and to maintain precise definitions of the units of the system of measurement, to decide what is to be measured, to know and to control the



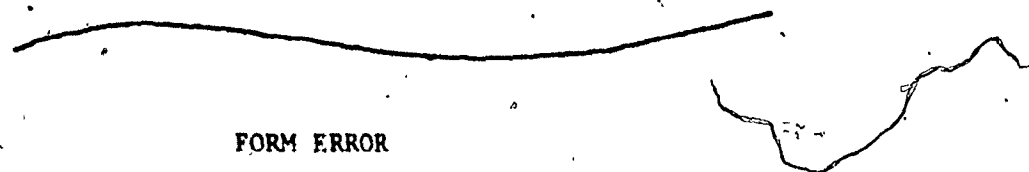
SURFACE PROFILE



ROUGHNESS



WAVINESS



FORM ERROR

FIGURE 13. SURFACE TEXTURE REPRESENTING THE
COMBINED EFFECTS OF THREE CAUSES

uncertainties associated with the measurement, and to provide a meaningful, usable representation of the measurement.

Over the last three decades or so, the manufacturing industry has been increasingly concerned with the subject of surface roughness measurement. It is the result of a realization that improvement in surface finish often leads to improved performance and increased life. Much research has been done on the influence of surface roughness on lubrication, resistance to wear, load-carrying capacity, tool life, resistance to corrosion, fatigue resistance, ability to hold pressure and noise reduction. Various methods of measuring roughness have been used in investigations and many instruments have been developed for this purpose. The usual concept of roughness is sensory, that is, it is evident mainly to the senses of sight and touch. It has, therefore, been difficult to define surface roughness in terms of measurable attributes.

Any machined surface will always have some roughness. Abrasion processes, such as lapping and honing, produce irregular and multi-directional textures. Grinding, the most widely used finishing process, generally gives a texture which is irregular but unidirectional. Textures produced by cutting processes like turning, boring and shaping tend to be both evenly spaced and unidirectional. Each machining process has a typical effect on the nature of the surface produced. Hence, when a specification is made for the required surface finish, it is also necessary to specify the machining or finishing process.

Every surface created by a chip-removal machining process is rendered imperfect due to a variety of reasons, which can be classified into four orders of geometrical irregularities:

- First Order: -Irregularities due to inaccuracies in the machine tool, lack of straightness in the slideways, deformation of the work-piece under cutting forces, etc.
- Second Order: -Irregularities caused by vibration and chatter.
- Third Order: -Irregularities caused by the machining itself and process characteristics.
- Fourth Order: -Irregularities due to lack of surface integrity, rupture of material during the separation of the chip, etc.

Not all surfaces are created by the chip-removal process, but the above four orders give us some useful ideas about causes of surface roughness. The first and second orders of irregularities constitute the waviness and form errors of the surface, and may be termed macro-geometrical errors. The third and fourth orders of irregularities constitute roughness, and may be termed micro-geometrical errors.

The first problem associated with any system of surface measurement is that of selecting a suitable reference from which the measurement is to be taken. Two possible references seem automatic choices: -

- a) In order to draw a straight line through a set of points defining the profile, one should apply the principle of least squares so that the reference line may be regarded as the line which reduces the sum of the squares of the deviations to a minimum. This is called the mean line, and it divides the section in such a way that the sum of the areas above and below it are equal and a minimum-

b) A line touching the peaks of the profile, that is an envelope line which defines the macro-geometrical form.

These two systems of drawing reference lines in order to assess numerical values of surface roughness are called the M-System and E-System respectively. The advantages of one system over another is not a matter of universal accord, however, and therefore, both systems have been in extensive use.

M-System

It is clear from Fig. 14 that a mean line through the whole section AB may not give a very useful representation of the surface roughness. A better indication will be obtained from the average of a number of consecutive samples of length L .

Consider Fig. 15, and let the curve describing a sample section be in the original coordinate system (x_1, y_1) , conveniently defined by a stylus probe type instrument. If the area bounded by the curve, the x -axis and the sample length ordinates is measured to be A , then a line ab can be found from the relationship $a = \frac{A}{L_1}$, such that the sum of the areas above it is equal to the sum of the areas below it.

Let the shaded area lying above ab be A_1 . Now if the coordinates are rotated through an angle θ_2 to give a new coordinate system (x_2, y_2) , a new line $a_2 b_2$ may be found which will have an area A_2 lying above it. In this manner, a series of values for A corresponding to a series of values of θ may be found and by graphical interpolation the value of θ which gives the minimum area A , may be determined.

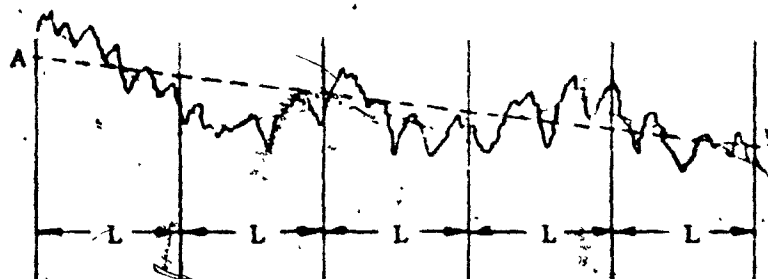


FIGURE 14. SURFACE PROFILE SHOWING MEAN LINES
FOR THE WHOLE LENGTH AND
CONSECUTIVE SAMPLE LENGTHS

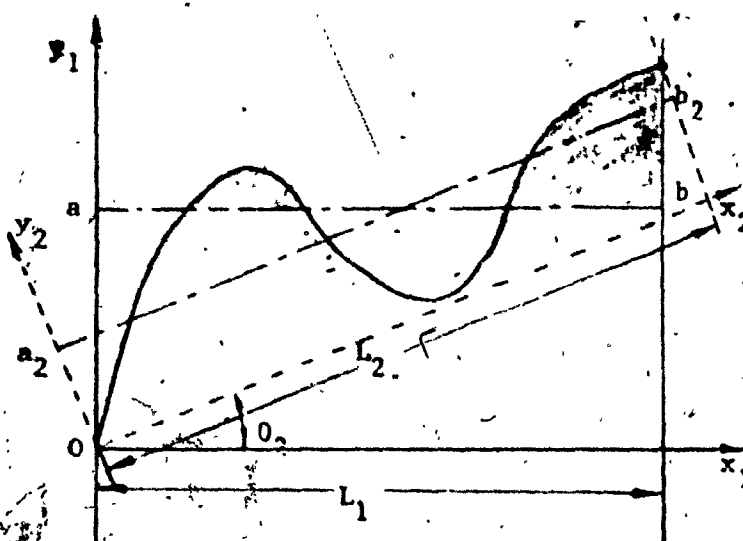


FIGURE 15. MEAN-LINE DETERMINATION

This procedure is obviously tedious and will present difficulties in measurement and computation. Consequently, the definition of the mean line is relaxed to that of the centre line, which is taken to be parallel to the general direction of the profile, and such that the sums of the areas contained between it and those parts of the profile which lie on either side of it are equal.

In practice, several roughness measures have been found to be useful and have been utilized in suitable applications. Broadly, these are: -

- a) maximum peak-to-valley height
- b) average roughness
- c) form factors and bearing curves.

Maximum peak to valley height R_t

This is the simplest measure of roughness, but it is an incomplete definition. Fig. 16 represents two surfaces in which the total height of the irregularities is the same.

However, this is a useful measure for controlling the cost of finishing a rough-machined workpiece.

Average Roughness

The most widely accepted criteria have been the arithmetical average deviation of the points in the section from the centre line and the root mean square deviations from the centre line. The deviation R_a is called the "Centre-Line Average" or CLA value. Fig. 17 shows a short sample section of a surface profile with graphic representation of the parameters used.



FIGURE 16. MAXIMUM PEAK TO VALLEY HEIGHT R_t

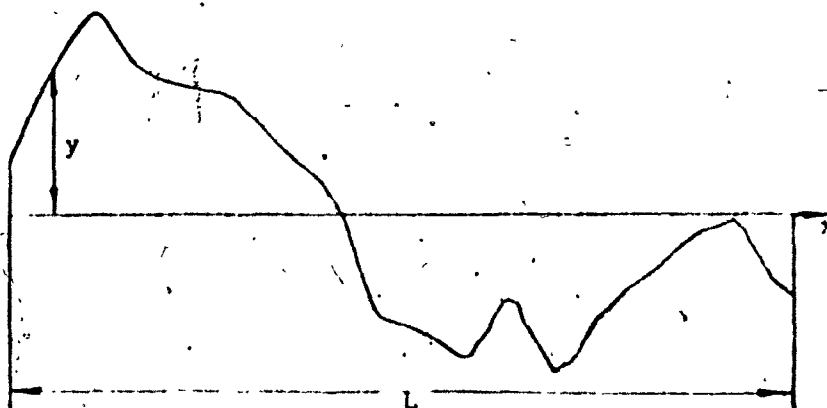


FIGURE 17. CENTRE-LINE-AVERAGE DETERMINATION



FIGURE 18. TWO SURFACE CONTOURS WITH THE SAME AVERAGE DEVIATION

The centre line average deviations are defined by the equations:

Arithmetic Average $R_a = \frac{1}{L} \int_0^L |y| dx$

RMS Average $R_a = \sqrt{\frac{1}{L} \int_0^L y^2 dx}$

Many earlier surface measurement systems, employed the tracer method, yielding the root-mean-square average. On a given surface, this value would be approximately 11% greater than the arithmetic deviation.

The arithmetical average deviation has been favoured most because it presented the least amount of measurement and computation problems.

These methods, unfortunately, do not indicate the actual profile of a surface. A sinusoidal surface would give the same reading on a roughness meter as a surface consisting of a series of sharp cusps as shown in Fig. 18. But these surfaces can be expected, to have quite different mechanical properties. An obvious improvement over this simple average type of reading is to display the profile of the surface in graphical form. How accurately this can be done so that an effective control action may be taken, is however, a continuing problem.

Form Factors

The load-carrying area of a finished surface is generally much less than is apparent. Formfactor is a measure of this characteristic and is defined as

$$K = \frac{\text{Area of metal}}{\text{Area of enveloping rectangle}}$$

Bearing Area Curve (Abbott Bearing Curve)

This is determined by adding the lengths a, b, c , etc., at depths x, y, z , etc., below a reference line indicating the percentage bearing area which becomes available as the peaks are worn away (Fig. 20).

Other Measures

Several variations of the GLA measure are in use in different countries. For example, ISO Recommendation R468(1966) gives the Ten-point Height R_z as a useful measure (Fig. 21), where the mean difference is taken between the five highest peaks and the five lowest peaks.

$$R_z = \frac{(R_1 + R_3 + \dots + R_9) - (R_2 + R_4 + \dots + R_{10})}{5}$$

In Germany (DIN 4762), maximum peak-to-valley height R_t within the sampling length is used as a surface finish measure within short sample lengths.

The Swedish method is based on peak and valley intercepts, as shown in Figure 22. The measured value R_{sm} is such that $\Sigma P = \frac{L}{20}$, and $\Sigma V = \frac{L}{10}$.

Since none of these measures describe the actual profile of a surface, a close graphical representation of the surface has been a subject of extensive research and development through the years.

The assessment of surface roughness by stylus methods has been in use since the early 1940's and the basic principles and parameters to be controlled are the subject of many national and international standards.

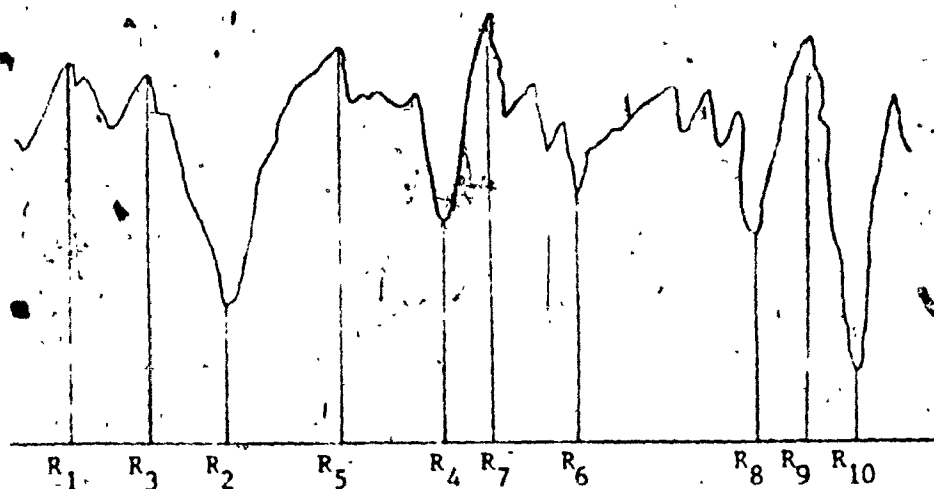


FIGURE 21. TEN-POINT HEIGHT



FIGURE 22. PEAK AND VALLEY INTERCEPTS

The most commonly used type of instrument for measurement of surface finish has been one in which a pick-up carrying a sharply pointed stylus is traversed along the surface by a motorized drive. Vertical movements of the stylus relative to a skid which is used to guide the pick-up over the workpiece, are converted by a transducer into corresponding changes in an electric signal. These changes are then amplified and used to drive a strip-chart recorder.

As long as the tip of the stylus is smaller than the smallest surface irregularities, it would faithfully reproduce a magnified cross-section of the surface profile. But in practice, such a small stylus tip is hard to produce and consequently the accuracy of this measuring technique has been restricted.

Moreover, the skid or shoe supporting the stylus may not produce an accurate reference line while sliding on an irregular surface. Many different shapes of skids and a variety of skid-stylus mechanisms have been developed to overcome the problem. The skid or the shoe, however, provides the surface reference and not a true reference. If long range variations in the surface macrostructure are desired in addition to surface roughness, it is obtained by the use of a device which measures the deviation with respect to a fixed reference line instead of the skid.

E-System

In Europe, interest in the envelope line of the actual surface as a reference line has grown to a great extent. It is claimed that it constitutes a more satisfactory reference than the CLA system.

In the E-system, an envelope profile traced by a rolling circle of specific radius is used as reference line. This procedure is extended further for the definition and measurement of waviness and form errors with an appropriate value for the rolling circle in each case. In such a system, the separation of roughness from other errors, is controlled solely by the shape of the reference line produced by the rolling circle. Thus the value of the rolling circle radius r_e has to be standardized, with care as being the most important parameter in the measurement of roughness under the E-system.

The difficulty, assuming that the radius r_e has been satisfactorily standardized, is that different envelope curves will result from different directions of approach of the rolling circle. This is illustrated in Fig. 24, which shows that the envelope profile (2) for direction of approach y_2 differs from the envelope profile (1) for direction of approach y_1 . The surface profile is produced by an instrument which fixes the X and Y coordinates by directions of the movements of the instrument and the position of the envelope in these coordinates is fixed by the position of the work. Curves of this kind would not indicate the position of the actual surface relative to the ideal surface. The best that can be done is to replace the ideal surface by a line passing through the total length of the actual profile. This is hardly a more refined procedure than that adopted for placing the centre line in the M-system. However, if the X and Y coordinates can be fixed with certainty and if an optimum rolling circle radius can be selected, the E-system provides a fairly simple way for providing a description of the profile.

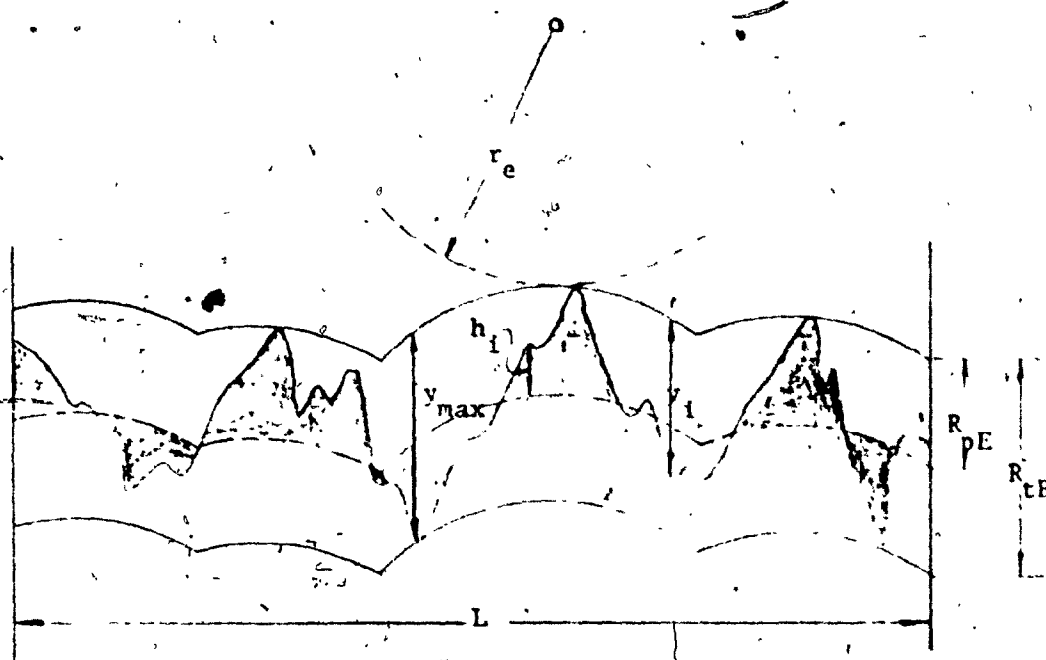
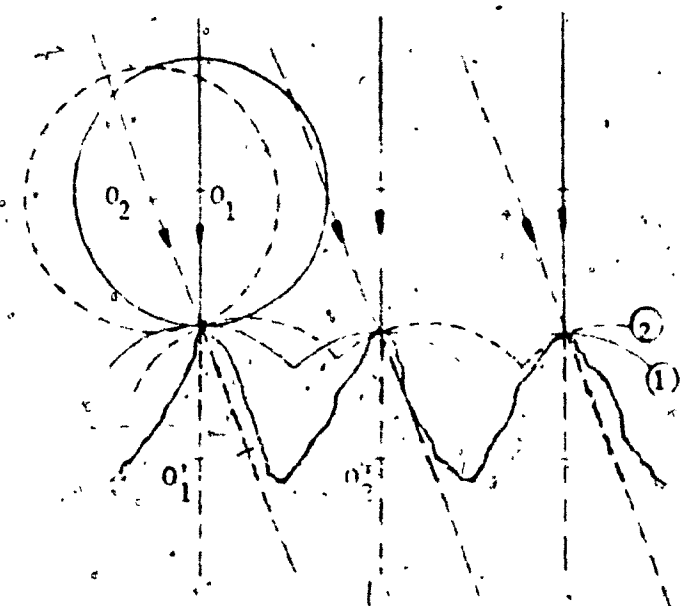


FIGURE 23. ENVELOPE SYSTEM

FIGURE 24. ENVELOPE PROFILES WITH DIFFRENT
DIRECTIONS OF ROLLING-CIRCLE APPROACH

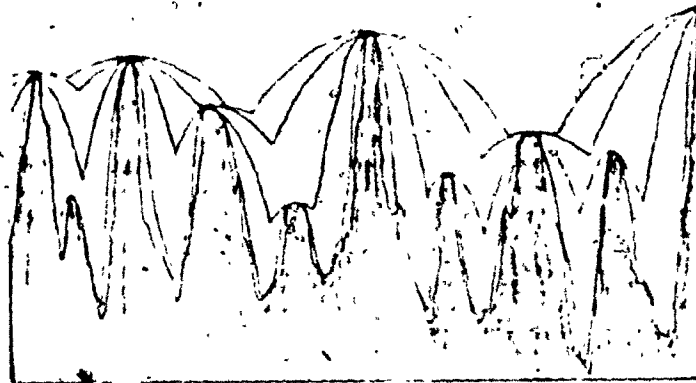


FIGURE 25. PROFILE OF A TURNED SURFACE WITH
ENVELOPES OF DIFFERENT ROLLING
CIRCLE RADII. (29)

Magnification: Vert 3000 Hor 100

Various methods of statistical analysis of profile envelopes have been introduced with the help of digital computers (15). For such an analysis, surface profiles are normally traced with a stylus using a fixed datum attachment, and the data obtained from the instrument are digitized for storage. A typical programme would compute envelope profiles with different rolling circle radii, selecting those peaks which were likely to influence the envelope. Various roughness parameters are then determined according to the E-system. Fig. 25 depicts a typical turned surface profile with envelope profiles obtained with different rolling circle radii: (29).

It will be noted from Fig. 25 that the envelope circles are not perfect circles but distorted to some extent. Commercially available instruments provide different scales of vertical and horizontal magnification since actual vertical deviations are extremely small compared to horizontal distances. The rolling circles are, therefore, distorted into ellipses and the arcs touching the peaks of a profile curve become arcs of an ellipse.

Comparison of "M" and "E" systems

A strict comparison of the roughness values obtained in the "M" and "E" systems is not simple. The irregular nature of the profiles is mainly responsible for the problem. However, the most suitable parameter for comparison is the R_a value. A condition has to be found for obtaining the same R_a value in both systems by selecting a suitable meter cut-off and envelope radius. Meter cut-off or wavelength cut-off is a convenient representation of sampling length

and standard values recommended in British Standard BS 1134 are 0.003, 0.01, 0.03, 0.10, 0.30 and 1.0 inch. Usual cut-off values in international standards are 0.25, 0.75 and 2.5 mm. From experiments, 0.03 inch and 0.75 mm have been found to be most suitable for a wide range of surfaces.

For comparison purposes, R_{AM} values may first be found for a profile after computing the centre line for three cut-offs, e.g., 0.25, 0.75 and 2.5 mm. Then the R_{AE} values are computed for the profile with different envelope circle radius. From these R_{AM} and R_{AE} values for the profile, an envelope circle radius r_e can be found for each cut-off which gives the same R_a value. This experiment should be carried out on a large number of profiles in order to obtain meaningful results. One such experiment has given the practical optimum cut-off and r_e values as 0.75 mm and 3.2 mm respectively (29). It has also been found that the effective separation of waviness takes place at or near the optimum envelope circle radius.

A ground surface profile, together with its "M" and "E" system mean lines is shown in Fig. 26. The "E" system mean line is obtained by shifting the envelope by an amount R_{pE} (Fig. 23). The "M" system mean line is obtained when the measured signal representing the profile is passed through a RC filter which eliminates the lower frequencies constituting the waviness. The amount of filtering will depend on the cut-off value selected for the filter. If the cut-off value is small, the mean line will be closer to the profile, but as the cut-off increases, the mean line becomes smoother. With infinite cut-off a straight mean line should be obtained.

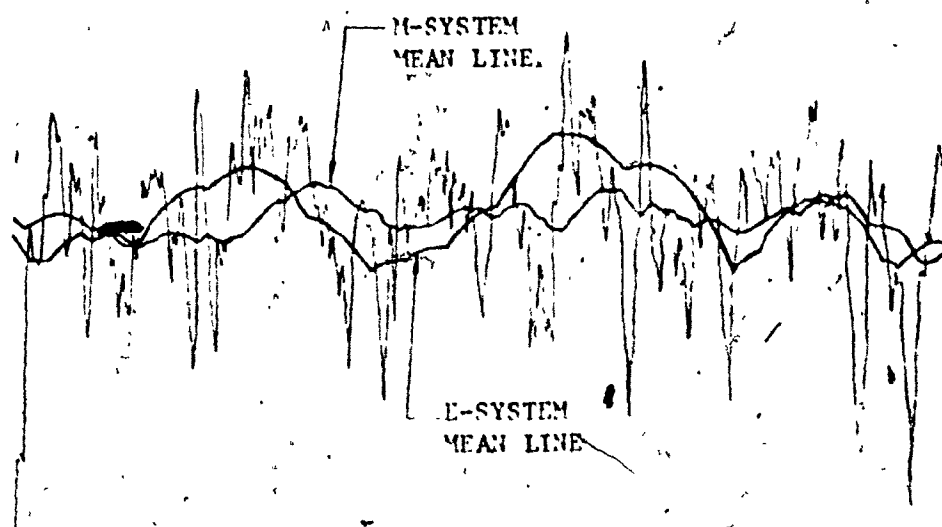


FIGURE 26. M-SYSTEM AND E-SYSTEM MEAN LINES FOR A@
GROUND SURFACE PROFILE (29)

Cut-off 0.75 mm r_e 3.2 mm

Magnification V 8000 H 100

CHAPTER 7

STATISTICAL ANALYSIS OF SURFACE FINISH

7.1 Introduction

It has been recognized for a number of years that a single roughness parameter cannot effectively describe the surface characteristics. It was found necessary in the automobile industry not only to apply limits to R_a but also to classify the type of surface from its profile (28). The American automobile engineering standard SAE J911 specification for sheet steel calls for a control on the peak count per unit length of surface (28). Others have suggested measurement of openness or closeness of surface texture on automobile sheet steel bodies in addition to specifying R_a (28). All recommendations broadly point toward the need for an analytical description of the profile based on the random characteristics of all surface profiles.

For analytical purposes, a surface profile is separated into two components. One is a function of the roughness height or amplitude of the waveform. The other represents the toolmark spacing or wavelength. Statistically, these two components of the waveform may be described by amplitude distribution and auto-correlation function respectively.

7.2 Amplitude Distribution

The amplitude distribution is shown in Fig. 27. It is determined by plotting the number of ordinates which occur at different levels through the surface, and for many practical surfaces the distribution is Gaussian (Fig. 27a). One of the features of the distribution curve which cannot be

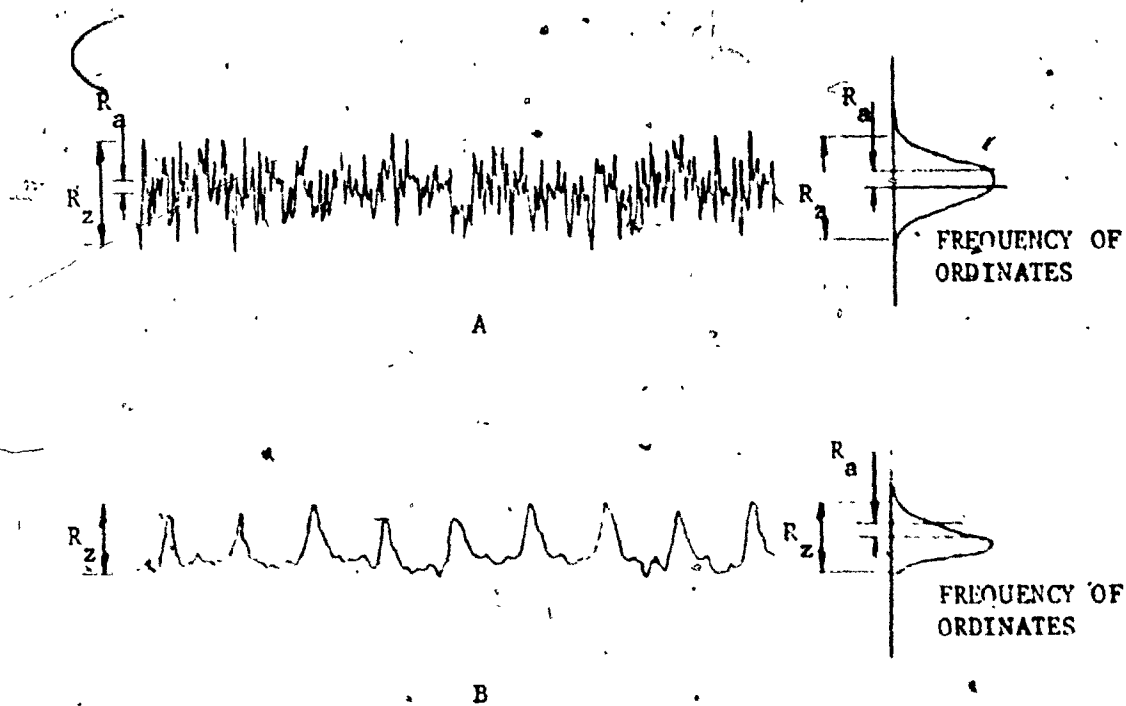


FIGURE 27. AMPLITUDE DISTRIBUTION (28)

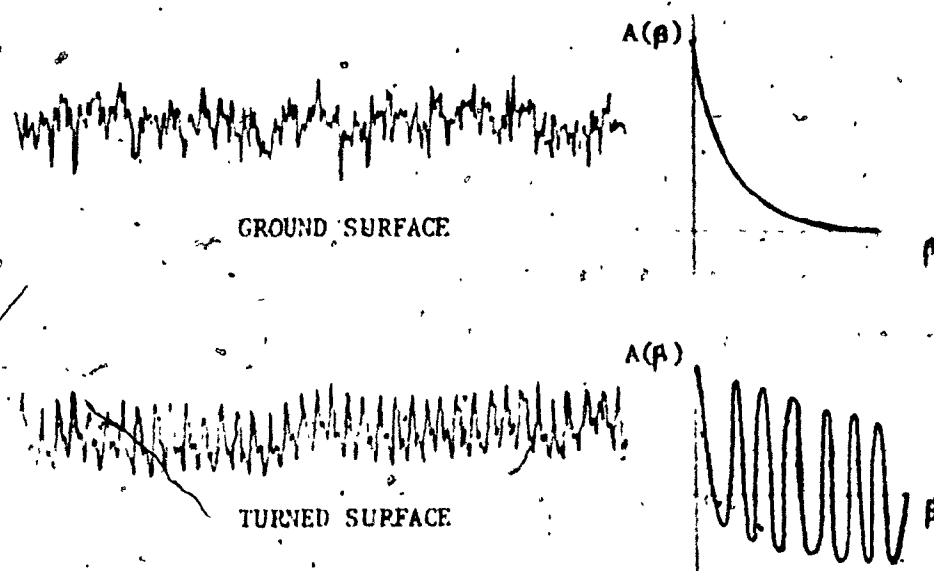


FIGURE 28. AUTO-CORRELATION FUNCTION (28)

measured by the conventional stylus-probe type instruments is the skew of the curve which may be seen by comparing Fig. 27b with Fig. 27a. A good approximation to the amount of skew may be obtained by taking the difference between the average peak and the average valley measured from the mean line, divided by R_a to normalize the result.

One of the standardized parameters which may be measured from the amplitude distribution can take account of wavelength, and it is now generally recognized that information related to wavelength is of great importance in surface roughness measurement in order to predict the behaviour of the surface under load. Statistically, this may be obtained from the auto-correlation function.

7.3 Auto-correlation of a Profile

The auto-correlation function $A(\beta)$ characterizes the dependence of the measured profile amplitudes $f(x)$ on $f(x + \beta)$ where β is measured along the surface. In other words, $A(\beta)$ is the expected value of $f(x)f(x + \beta)$ averaged over sample length L .

$$A(\beta) = \lim_{L \rightarrow \infty} \frac{1}{L} \int_0^L f(x)f(x + \beta) dx$$

As L tends to infinity, the average tends to the true auto-correlation function. $A(\beta)$ is always a real, even function with a maximum value at the origin.

Fig. 28 shows two correlograms of surfaces produced by different machi-

ning processes. Correlograms show the degree of correlation or dependence of one ordinate in the profile on others at given distances β from it.

The auto-correlation functions of the "M" and "E" system mean lines in Fig.26 together with that of the profile are shown in Fig.29. It shows that the randomness involved in the mean lines is not as high as that of the profile. The longer waves separated by filtering are shown in the correlograms of the mean lines. As the envelope is controlled by the few prominent peaks of the surface profile, the remarkable coincidence between the waviness of the envelope and that of the mean line indicates that even in the case of random profiles without any periodicity, the waviness is clearly determined by the prominent peaks. Of course r_c should also be selected in such a way that the envelope makes contact with those peaks which control and define waviness (29).

7.4 Power Spectral Density and Average Wavelength

The frequency distribution of the surface may be obtained from a correlogram by taking the Fourier transform of the auto-correlation function:-

$$P(\omega) = \frac{1}{\pi} \int_0^{\infty} A(\beta) \cos(\omega\beta) d\beta \quad \text{where } \omega = \frac{2\pi}{\lambda}$$

$P(\omega)$ is called the Power Spectral Density or Power Spectrum.

An extremely powerful and practical control parameter was suggested by Spragg in 1968 (39) and later developed by Spragg and Whitehouse (28).

It is the average wavelength λ_a which may be found by taking the ratio of R_a to the average slope.

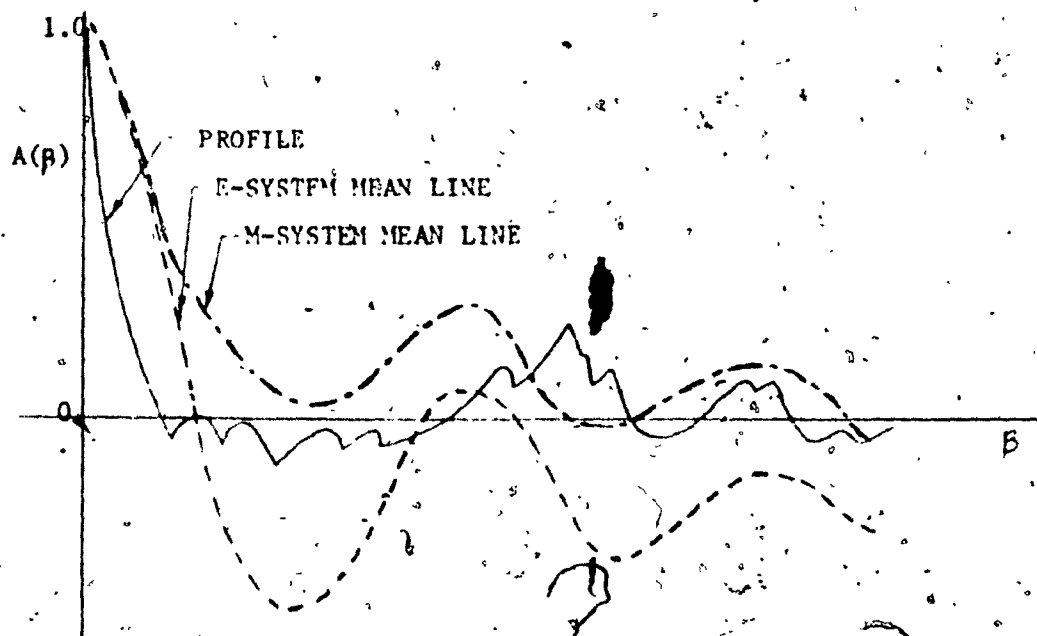


FIGURE 29. AUTO-CORRELATION FUNCTIONS FOR A GROUND SURFACE PROFILE, ITS M-SYSTEM MEAN LINE AND THE ENVELOPE (29)

$$\lambda_a = 2\pi \frac{\int_0^L |v| dx}{\int_0^L |v|^2 dx}$$

A detailed mathematical treatment of average wave length may be found in reference (28). Fig. 30 shows how λ_a relates to the Power Spectrum for some typical machined surfaces. R_a and λ_a measured over a given range of frequencies offer a relatively new approach to specification and measurement of roughness.

The following table gives R_a and λ_a values for some typical machining processes (28).

Process	λ_a μ	R_a μ
Planing	400	17.8
Multiple tooth milling	1300	5.1
Turning	100	1.7
Flat grinding	77	0.95
Circumferential grinding	31	0.55
Honing	19	0.03

Because of the presence of a large number of very short wave length components, some random profiles are difficult to assess in terms of λ_a . Some rejection of these short wave lengths is necessary. In practice, the limitation of stylus tip radius effectively acts as a filter. The longer wave lengths are excluded by limiting the sampling length. Surface roughness measuring instruments are also designed to reject long wave lengths resulting from machine vibration and form errors.

7.5 Application of Average Wave length parameter

To demonstrate how the average wave length measurement is profitably applied in surface finish control, two periodic turned surface waveforms with same R_a and λ , but different λ_a values are shown in Fig. 3.

In case of a turned surface with a second order random waviness, λ_a is found to be equal to the feed mark of the tool even when the feed rate is not apparent from the waveforms.

7.6 General remarks

It has been well established that a machined surface profile is a stochastic function. Measurement and control of surface finish, therefore, involve sensing and processing certain parameters giving a probabilistic description of the profile. We have seen that a measure of the average height of the surface irregularities is insufficient to control the behaviour of the surface. So far Power spectrum or Average wavelength have provided a powerful additional control parameter that is dependent upon the wavelengths making up the surface. A lot of research work has been done and is continuing towards providing useful measures suitable for effective/on-line control of surface finish.

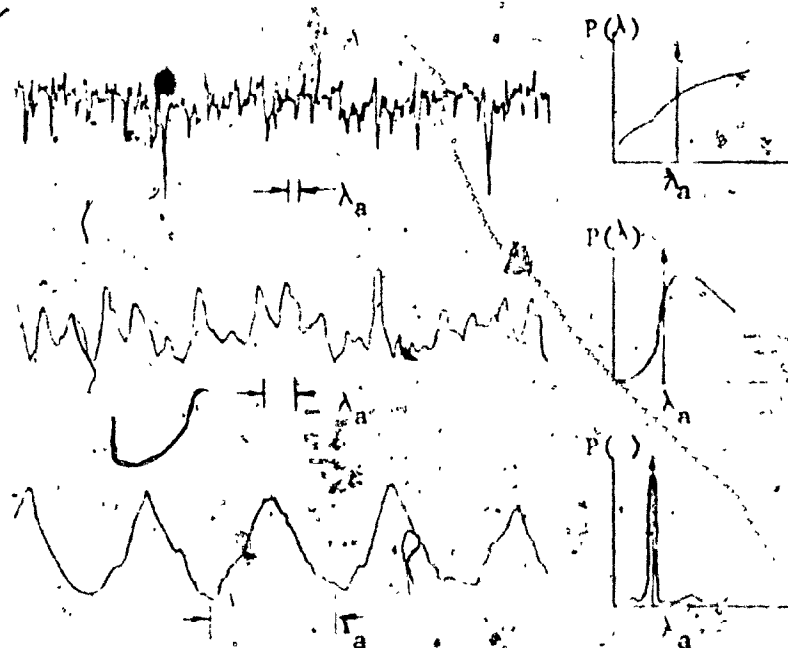


FIGURE 30. POWER SPECTRUM AND AVERAGE WAVELENGTH (28)

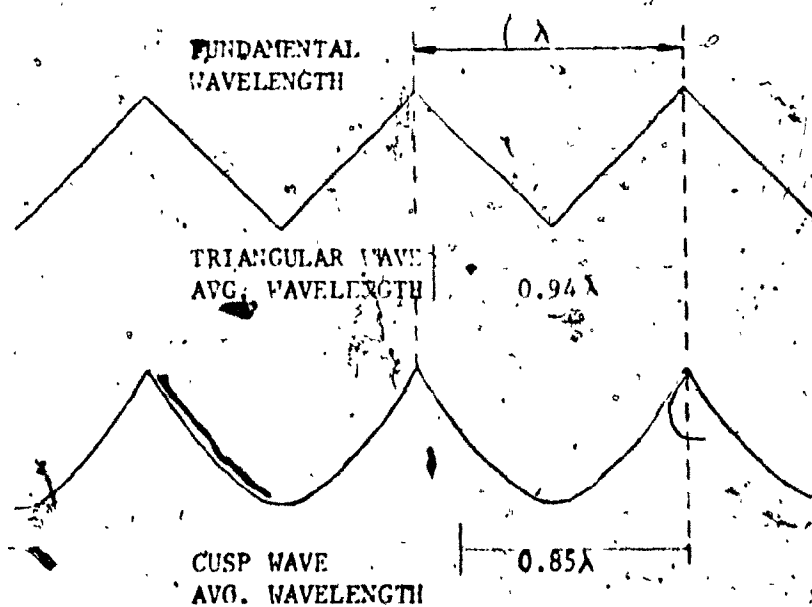


FIGURE 31. COMPARISON OF FUNDAMENTAL TO AVERAGE WAVELENGTH (28)

CHAPTER 8

SURFACE FINISH MEASURING INSTRUMENTS

8.1 Introduction

In the previous two chapters, definitions in terms of surface metrology and statistical descriptions of surface profiles were presented in order to have a clear understanding of what we wish to measure and control. Although the greatest accuracy results from analytical or graphical treatment of the actual surface profile, under production conditions, we must consider use of suitable commercial instruments for determination and processing of various measures of surface roughness.

Prior to development of modern measurement techniques, surface finish was assessed by visual and tactile senses. Modern instruments also perform the measurement tasks utilizing basically the same concepts. A partial list of methods used for surface finish measurement will confirm this statement,

1. Tracer Method, which employs a fine stylus moving across the surface. In spite of its many limitations, it is still the most widely used method for obtaining quantitative results.
2. Visual comparison with a standard surface. This method is more concerned with appearance and does not provide any usable measure - More an inspection technique than a measurement method.
3. Plastic replica method (34), wherein a soft, transparent plastic film is pressed onto the surface and stripped off. Light is then passed through the replica and measured. Refraction caused by the rough surface reduces transparency and integrity of transmitted light is used as a measure. Not suitable for production conditions.

4. Reflection of light from the surface measured by photo-electric sensors.
5. Magnified inspection, using electron microscope.
6. Parallel-plane clearance, leakage of low viscosity liquid or gas between the subject surface and a reference flat is used as a measure of roughness.
7. Laser Interferometry, using the wave length of light as a standard in measuring a surface.
8. Laser Holography, a technique of three dimensional photography, displaying and measuring the irregularity of a surface.

In spite of rapid advances made in the field of optical measurements, which are expected to provide high-resolution interpretation of a random profile, suitable commercial equipment for on-line utilization in a manufacturing environment is lacking. Consequently, the stylus-probe type of sensors, together with sophisticated electric transducers have most commonly been used in the industry for on-line applications.

8.2 Stylus type instruments

One of the best known stylus type instruments is the TALYSURF developed by Rank Precision Industries of Leicester, England. Although the instrument has evolved through many stages of development, its fundamental principle has remained virtually unchanged.

In its basic configuration, a sharp stylus traces the surface profile and the resulting vertical oscillations of the stylus are converted into corresponding modulations in a carrier electrical signal. The distorted carrier signal is then amplified and filtered with a waveform analyzer. An average meter computes the

average reading from the signal for a preset cut-off or sample length. The signal is also processed separately to give a true representation on a strip-chart recorder. The datum for average readings or profile graphs is generated within the instrument, irrespective of the nature of the surface. A variety of datum attachments are available to give the most suitable reference lines for many types of practical surfaces.

Different models of TALYSURF offer a wide range of options, notable among which are large meter cut-offs and suitable filter circuitry for measuring waviness, and meters for computing statistical parameters like average wavelength and average slope of the profile.

Perth-o-meter is a similar stylus instrument of German origin, which has a number of tracer arrangements to suit different kinds of surfaces. The instrument gives indications of all the standard surface finish designations, - the peak-to-valley height, waviness, arithmetic or RMS average roughness or for both waviness and roughness at any depth.

The limitations of the stylus type instruments are obvious from their brief descriptions. The accuracy of measurement is dependent upon the size and shape of the stylus tip which acts as a mechanical filter to very fine surface irregularities. The accuracy of the transformation of stylus oscillations to electrical signals depends on the stylus spring pressure which in turn influences friction forces between the stylus and workpiece. A stylus tracer installed on the machine tool will be subject to random tool-workpiece vibration, adding to the inaccuracies.

in stylus oscillation. The recorded profile graph, although providing a visual display of a close approximation of the actual profile, does not give any useful data for direct utilization in the control system.

All modern stylus instruments, therefore, provide statistical representations of the surface profile in addition to conventional average readings. Off-line inspection of surfaces with Talysurf, Perta-e-meter, Profilometer and other similar instrument set-ups therefore include separate recorders for amplitude density, autocorrelation function, average wavelength, average slope or bearing area curve.

The importance of a suitable stylus geometry for tracing a particular surface is illustrated in Fig. 32. The ability to climb out of the valleys requires a large enough included angle α as well as always having line BC above the highest peak in the profile to prevent the stylus from totally lodging. On the other hand the distortion of the profile recording will depend upon the angle α as the approximate profile will be represented by the stylus tip sides AC and AB. A fine stylus with a small included angle could solve the problem but would not be able to trace rough surfaces or surfaces with deep scratches. Oscillating stylus systems (33) overcome this difficulty in a simple manner.

Although developed for the purpose of measuring highly irregular surfaces such as abrasive tools, the field of application for oscillating stylus can be far wider. The instrument uses a stylus attached directly to the core shaft of a displacement transducer. The stylus is oscillated by a motor-driven cam thereby moving the transducer core to produce a D.C. voltage proportional to the core displacement. If this movement is not restricted, the voltage produced by the transducer is sinusoidal with respect to time.



FIGURE 32. STYLUS GEOMETRY

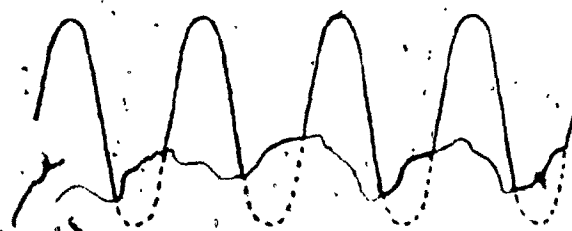


FIGURE 33. SURFACE TRACING PRODUCED BY AN
OSCILLATING STYLUS MECHANISM (30)

When this movement is restricted by a surface, the sinusoidal signal is partially truncated as illustrated in Figure 33. With higher and higher oscillation frequency, the true representation of the actual surface is approached.

Transfer of the profile data for analysis cannot be done in the conventional way, since the continuous signal produced contains information on the total movement of the stylus, of which only a portion represents the surface being measured. Thus an A/D converter cannot be used directly. To obtain a continuous recording of the restricting surface alone, the signal from the transducer must be conditioned. By using a passive peak detector, which consists of a diode, capacitor and resistor in series with a RC filter, a continuous signal is obtained. A series of RC filters would further refine the transformation of the signal. Figures 34 and 35 show the circuit and a system block diagram respectively.

8.3 Electro-Optical Instruments

In Chapter 5, an adaptive control system with a training loop using an electro-optical surface finish inspection device was described. Figure 36 shows how the instrument works (22).

The device is a commercially available instrument called Surface Quality Comparator (SQC). It operates with a high intensity light source optically collimated with pinholes and lenses such that a small spot of light is focused on the workpiece surface. The light is reflected from the

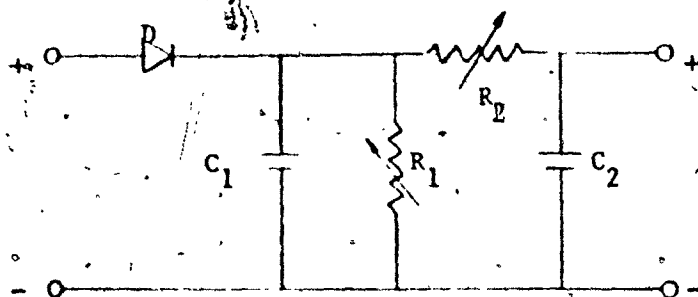


FIGURE 34. PASSIVE PEAK DETECTOR AND FILTER ASSEMBLY CIRCUIT

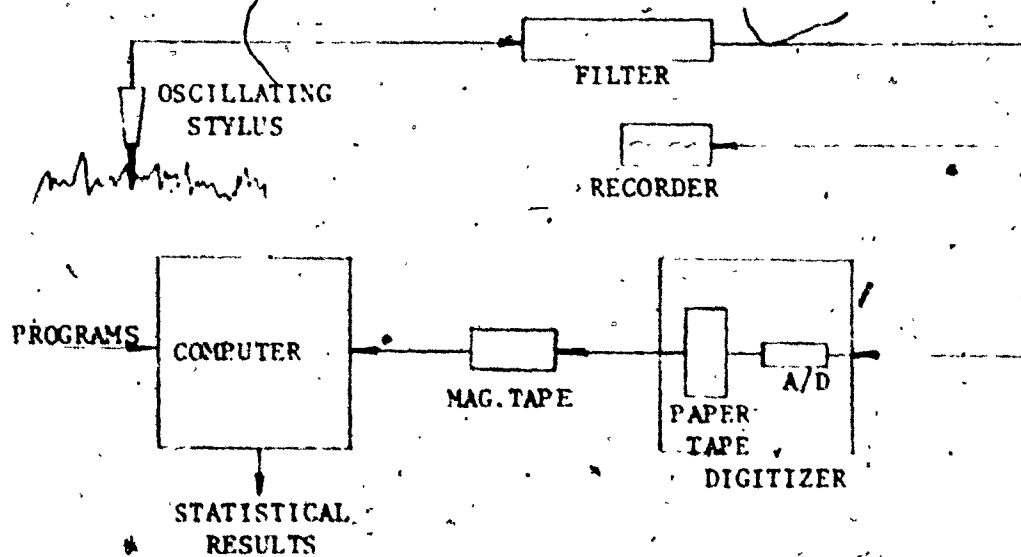


FIGURE 35. OSCILLATING STYLUS SYSTEM BLOCK DIAGRAM

surface and is mechanically chopped by a motor-driven slotted disc. The light is detected by a photocell which serves as the signal source for the electronic circuitry.

The circuitry processes the signal and produces a voltage proportional to the surface finish, i.e., the smoother the finish, the larger the voltage at the output of SOC. The shape of the photocell signal depends upon the type of surface. The signal is first differentiated, giving the light intensity distribution across the reflected light beam. Maximum slope of this signal varies with surface finish. After a second differentiation, a signal proportional to the slope of the intensity waveform is produced. The peak amplitude of this signal is proportional to the steepest slope of the intensity distribution signal, and is thus a direct indication of surface finish.

The signal is then digitized and fed to a general purpose minicomputer, where it is compared to a signal representing the on-line estimated surface finish. The deviation is used as a basis of updating or training the performance measurement function.

The design of the system is also suited for on-line adaptive control provided the machining operation time is long enough to make it worthwhile. But the major problems with electro-optical measurement are varying surface reflectivity and high sensitivity of the optical device to even minor vibration and chatter.

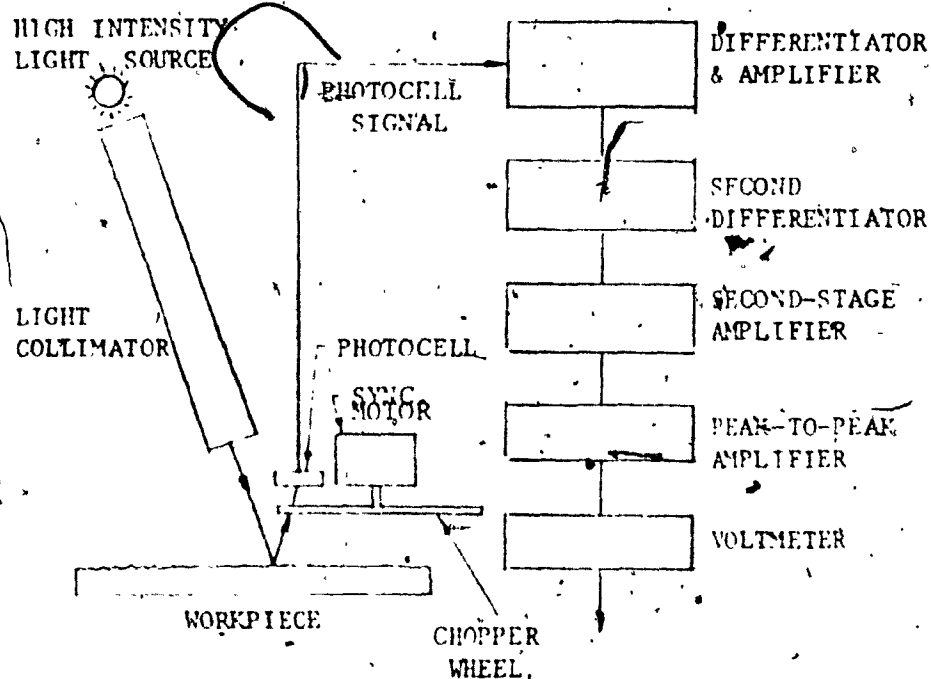


FIGURE 36. "SURFACE QUALITY COMPARATOR" SYSTEM

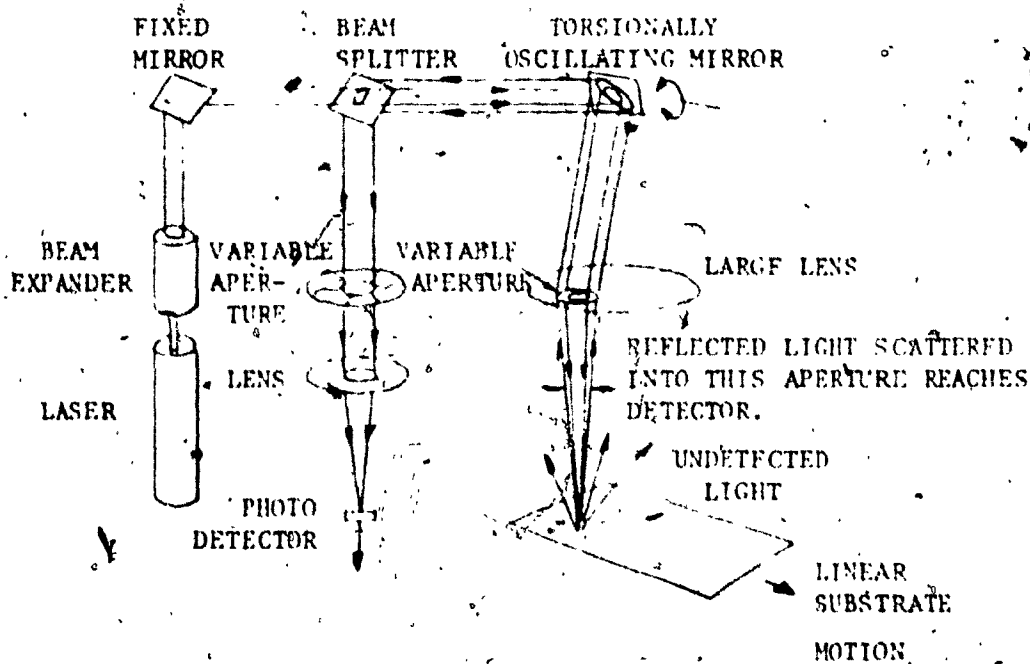


FIGURE 37. "FLYING LIGHT SPOT" SURFACE INSPECTION SYSTEM

Some compensation against vibration is achieved by mounting the instrument directly on the tool base, but the tool-workpiece vibration will still affect the reading. This vibration can be measured and automatic correction for its effects may be made by the computer, but for most machined surfaces the results may not be accurate enough.

Since light intensity is dependent upon the reflectivity of the surface, several adjustments will be required when the instrument is used on different shapes and types of material. Then again, nature of these adjustments probably have to be trial-and-error, contributing further to the inaccuracy.

A somewhat similar device, called a "flying light-spot system" is described in reference (16). A pictorial schematic of the system is shown in Figure 37.

A small 3 mW helium-neon laser beam is expanded and is incident upon a torsionally oscillating mirror. The mirror deflects the beam onto a lens which focuses it to a small spot. As the mirror oscillates, causing the expanded beam to scan back and forth across the lens, the focused spot effectively becomes a fine focused line. The surface being inspected is moved perpendicular to the scan line. Depending upon the surface finish there will be specular reflection, a diffuse reflection, or both. This reflection is detected and transformed into a usable signal.

The above scheme is obviously designed for a laboratory environment, although it can be modified for use on the machine tool also. Needless to say, the system then will suffer from the same disadvantages as mentioned in connection with the SQC system.

Scanning electron microscopes for laboratory inspection of surface finish and surface integrity have been in use for several years (25). But application of scanning microscopes for on-line inspection and signal processing has only recently been demonstrated (32). Its general arrangement basically follows the same electro-optical principles described earlier.

8.4 Laser Interferometers

Optical interference is the term applied to the combined effect of two or more beams of monochromatic light of the same wavelength, which, emanating from one source, are re-united after travelling along paths of different optical length. Interference between the re-united beams produces a series of bright and dark fringes whose separation depends directly on the wavelength of light. These interference fringe patterns are related to surface topography, when a laser interferometer is used to scan a surface.

As a surface is normally considered a 3-dimensional object, the conventional methods of measuring in one or two directions remain a limiting factor. Laser interferometry is applied not only for closer measurements but also for a three-dimensional study of a surface. Interferometry, however, will neither be the answer for all types of surface measurement nor

will it supersede all other methods. It is useful when results from non-contact methods are essential or unavoidable, or when it is more important to view a whole area rather than a line profile.

The basic instrument configuration is shown in Figure 38 (35). A laser's coherent light beam hits the beam splitter where half the light is diverted to a fixed reference reflector and the other half continues on to the surface being inspected. These two beams are then reflected back in their different paths, and recombined and diverted to photo-detectors.

The intensity of the recombined light depends upon the phase difference between the two parts of the beam when they re-unite, and this in turn depends upon the optical path lengths. If the optical lengths of the two paths are the same, or if they differ by a wavelength or an exact multiple of a wavelength, the two parts of the beam are in phase resulting in maximum intensity. But if the path lengths differ by half a wavelength or by an odd multiple of half a wavelength, the two parts of the beam are out of phase when re-united. Thus a change of only half a wavelength in one of the paths can cause the resulting intensity to vary from a maximum to a minimum. Irregularities on a surface thus cause changes in the reflected light's path length creating interference fringes of the types shown in Figure 39. The fringe patterns are transformed into analog signals or pulses by the detector and then processed in the conventional manner described earlier.

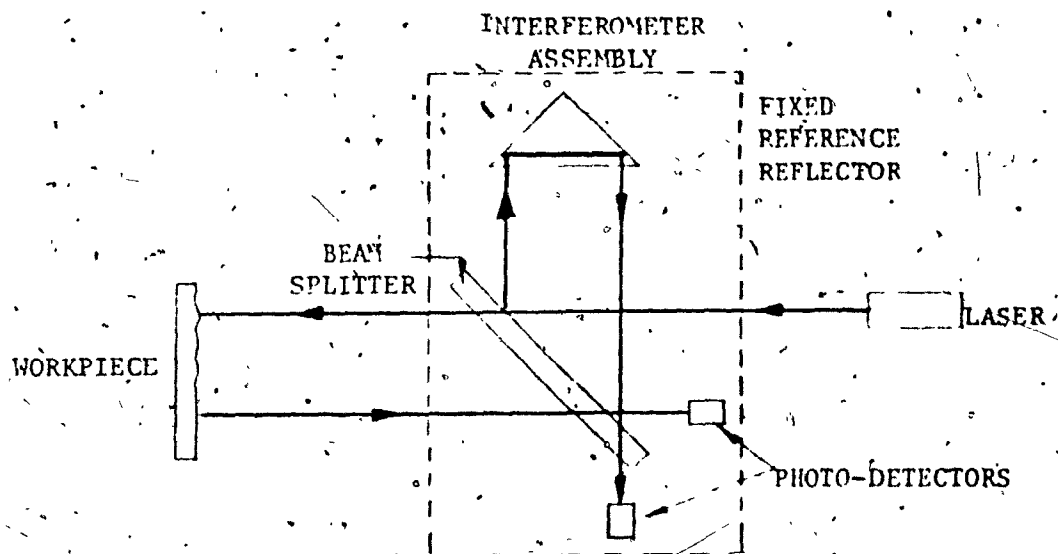


FIGURE 38. BASIC LASER INTERFEROMETER

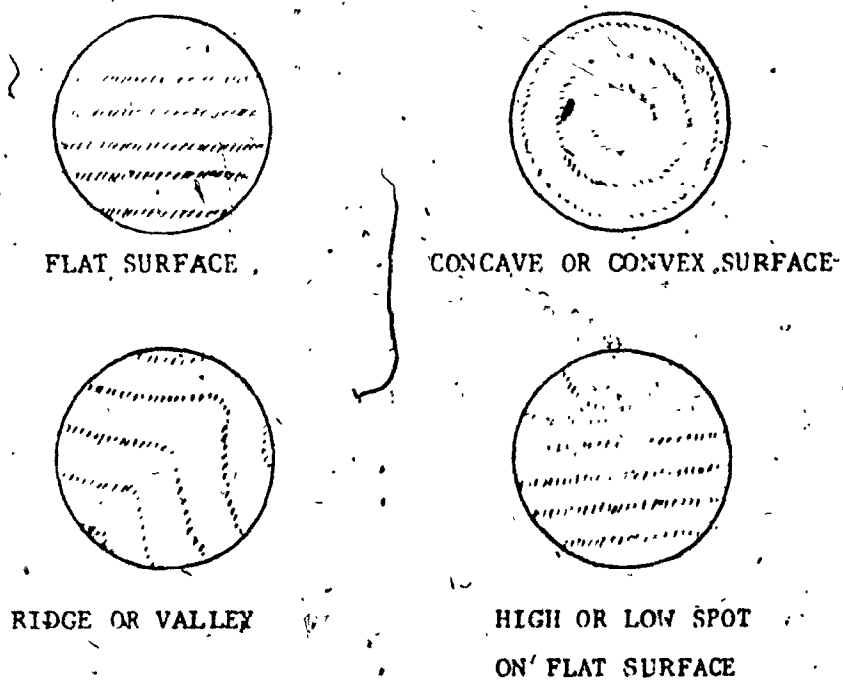


FIGURE 39. INTERFERENCE FRINGES

selecting good and bad pieces the control equipment would aim at making a larger percentage of pieces acceptable, with minimum scrap and labour cost. Most discrete part process steps produce a Gaussian distribution of values of any inspected specification measurement. Thus, if a measurement threshold is selected, above which or below which pieces are called good and bad respectively, it is an arbitrary and extensive selection.

Even the most perfectly understood process steps produce such a distribution for each kind of measurement. The same is true of measurement processes themselves. Any measurement system, if it measured the same piece over and over again, would show a distribution of readings, for inherent and similar reasons. It is therefore important to use a system which will automatically control the machine based on statistical averaging.

Figure 40 shows an interesting circuit arrangement which would be useful in automatic, graded-value measurement for feedback control of a machining process such as grinding, milling or turning, in which surface finish is to be measured and controlled (17). It could be used either during the machining step or after its completion, requiring only minor changes in the output portion of the circuit.

The input could be either from a laser measurement system or a stylus type probe. In both cases relative motion between the surface and the sensing location must be provided to scan the surface smoothly. The signal consists of electrical noise having two main components. Assuming constant relative speed, there is a broadband kind of noise resulting from causes such as laser

beam intensity variations, stick-slip type effects in rubbing contact of the stylus, vibration in the drive mechanisms and such. The useful part of the signal is confined to a relatively narrow band of frequencies determined by cutting traverse rate, gear feed unevenness, slideways errors, tool chatter etc. Filters eliminate or reduce part of the signal with frequencies outside the useful band. After filtering the problem is to separate useful signals from the remaining narrow-band noise, and the circuit in Figure 40 suggests a solution.

The quality which is used to distinguish the useful signals from the narrow-band noise is amplitude. For a very smooth piece, the narrow band noise is still present but low in amplitude. But chattermarks or machining ridges produce larger signals. It will therefore be hard to implement a fixed threshold type of filtering. The illustrated circuit automatically adjusts itself to avoid this problem. The circuit is patented by LFE Corp., Waltham, Mass.

The incoming signal is sent along two paths. In the upper path the signal is phase-split and fed as a differential signal to a differential input amplifier, into which only signals exceeding a bias threshold can enter. The bias voltage controlling this positive and negative threshold is produced in the lower signal path which rectifies and integrates the incoming signals. The level of this bias relative to average noise may be selected to fit the job in many ways. The bias input potentiometer setting and time constant of the bias integrator are selected so that as

the noise increases or decreases, it never can produce output from the differential amplifier. But a sudden positive or negative peak exceeds the running bias before the bias amplifier can develop enough signal to subdue it and passes through the differential signal amplifier as a significant signal.

The opportunities for automatically feeding information forward to the next step are many. One of the most economical way of utilizing the information would be to use the statistical measures. In quantity production, this would enable the manufacturer to tell the user of the next step what percentage of the pieces will be below and above certain stated deviations from the running average.

An examination of the physical facilities for optimal control of surface finish shows that the practical possibilities are quite limited at present. No matter what measurements are available to the controller, it only alters feedrate and spindle speed in response in accordance with some programmed adaptive routine. The whole question can now be redefined to ask what kind of optimization can be achieved with a system that is viable, or in other words, in what manner should the controller interpret the information received and how should it modify the controlled variables to get optimum results. The controller, equipped with the latest in electronic circuitry, should be able to follow advanced search strategies and look for the best combination of conditions, provided it has all the information in usable form and suitable routines relating the interacting variables. Although

CONCLUSION

In this technical report, we have attempted to demonstrate the importance of accurate on-line surface finish measuring instruments in adaptive numerical control of machine tools. In order to emphasize the need for improved measurement techniques, we provided a background of the modern machine tool control. Brief description of machining systems, numerical control technology, adaptive control systems and a recent history of the development of machine tool control has been provided for this purpose. Machining process variables and their behaviour with respect to each other have been treated briefly.

Surface finish metrology, statistical description of surface profile and development of relevant instrumentation have been discussed in general detail. The fact that surface finish control is not just for improvement of appearance, but for improvement of several vital mechanical and metallurgical characteristics has also been emphasized. While significant achievements have been made in development of instruments, the present state of the art is not adequate for complete adaptive control of machine tools. The basic measurement techniques, the stylus and electro-optical probes, have serious shortcomings as far as on-line application is concerned.

Future work, therefore, should be directed toward eliminating these shortcomings. Sophisticated control systems required for this improvement is already available. Another area requiring investigation is multivariable control as applicable to machining process. As in the past, the industry's necessities will prove to be the mother of invention.

12. M.C.Shaw, "Optimum selection of machine tool feeds and speeds", Proc. M.T.Design and Research, September, 1965.
13. J.Huber, R.Centner, "Test results with an adaptively controlled Milling Machine", Numerical Control for Tomorrow, University of Michigan, 1969, (Adapted from ASME Paper No.MS68-638).
14. F.K.Groszmann, A.V.Hemming, "Development of Adaptive Techniques to improve productivity of NC Lathes", Proc. 11th Int'l M.T. Des. and Res. Conf., 1970.
15. H.Kaliszer, D.J.Grieve, G.H.Rowe, "Digital Computation of Surface Topography", Trans. M.T.Des. and Res., 1971.
16. S.S.Charschan, "Lasers in Industry", Van Nostrand Reinhold, 1972.
17. G.F.Oultner, "Sensors in Automation", IEEE Trans. Ind. Electronics and Control Instr., February, 1974.
18. T.G.Schäin, "Stochastic Modelling of microgeometrical state of a manufacturing process", SGW M.Eng. dissertation, March, 1972.
19. J.Van Schynck, "Metal Machining", SGW M.Eng. report, April, 1973.
20. Kuang-Chun Lin, "The typology of a manufactured surface and its relation to the mechanical properties", SGW M.Eng. report, September, 1970.
21. T.R.Pryor, "Laser systems for industrial measurements", Canadian Controls and Instrumentation, October, 1973.
22. B.Feinberg, "Adaptive Control: Trainability adds a new dimension", Mfg. Engineering and Management, December, 1971.
23. K.Maddux, "Machine Tool Vibration", American Machinist Special Report, October, 1973.

34. L. Miller, "Engineering Dimensional Metrology," Edward Arnold, 1962.
35. R.W. Schede, "Built-in Interferometers", American Machinist
Special Publication "AM on NC", 1967.
36. J.B. Adolph, G. Norgate, "Holography in Engineering Applications",
Engineering Digest, June, 1972.
37. J.R. Parkinson, "Non-contact system measures rotating machinery",
Engineering Digest, September, 1972.
38. Air Force Machinability Data Centre, "Machining of High Strength
Steels with emphasis on Surface Integrity", Pub. No. AFMDC 70-1, 1970.
39. Conference on the Properties and Metrology of Surfaces, April, 1968,
Proc. Inst. Mech. Eng. 182, Part 3K, 1967-68.